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Department of Psychology

Las Cruces, New Mexico 88003

INFORMATION PROCESSING THEORY OF HUMAN PERFORMANCE AND RELATED RESEARCH

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A comprehensive theory of human information processing is presented along with four studies designed to test predictions based on the theory. The theory begins with a general definition of a task and then presents an approach for the prediction and evaluation of task performance. The first study compared reaction time, information transmitted and information transmission rate in detection, classification and identification tasks in an attempt to specify those stages in processing at which differences in these tasks occurred. Based on the data from this study, it was concluded that the three tasks differed in the response criterion

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(RC) portion of the a-component of the model. For the sake of parsimony it was suggested that no differences in higher level processing needed to be postulated to explain the data. The second study examined classification and identification tasks at various levels of stimulus and response information and found differences in RC between the tasks were primarily related to the number of stimulus and response alternatives. The data suggested that differences in the task existed even after differences in stimulus-response information had been taken into account. It was concluded that differences in classification and identification exist at stages of processing beyond the a-component. The third study examined the effect of stimulus compression in an information-seeking task. It was found that the effect of the compression of stimulus information depended upon the level of practice and whether or not the response to the stimulus required the creation (many-to-few translation) of information. The cost-effectiveness measure for the recoding of stimulus information was applied to the data. The fourth and final study examined temporal order and fusion judgments in an auditory task. The study factorially varied stimulus onset asynchrony and stimulus intensity. The results were interpreted in terms of the independent variables causing changes in the response criterion and psychological scanning rate of the a-component of the Teichner model.

Acknowledgments

This final report on Dr. Warren H. Teichner's Information Processing Theory of Human Performance has been brought to completion through the generous efforts of individuals associated with the Air Force Office of Scientific Research and individuals who were associated with the Human Performance Laboratory at New Mexico State University. Unfortunately, after having worked on his theory for a number of years, Dr. Teichner died prior to the completion of his research and the final write-up of his theory. This report presenting the theory and research of Dr. Teichner was completed after his death. While Dr. Teichner designed and supervised the conduction of most of the experiments included in this report, he was unable to contribute to the analyses of these experiments or to the interpretation of their results. Much of the work presented in this report is, therefore, a reconstruction of Dr. Teichner's ideas by other individuals who have worked with him over the last five years. Although the individuals who contributed to this report were familiar with his theoretical ideas and the concepts he was trying to examine in his research, the material presented here can only approximate that which Dr. Teichner had intended. As many of the details of Dr. Teichner's work could not be fully ascertained from the notes and papers which he had written prior to his death, these aspects of the research and theory are necessarily influenced by the hypotheses of those individuals who tried to complete the work in his stead. Consequently, it is doubtless that this report is missing many important points which Dr. Teichner would have tried to make.

Even with its limitations, this report represents a major accomplishment for which we gratefully acknowledge the encouragement and patience of the Air Force Office of Scientific Research which supported the project to its completion. In particular, we would like to thank Dr. A. R. Fregly, Program Manager, Directorate of Life Sciences, who monitored this effort for the Air Force Office of Scientific Research and Mr. R. L. Hann, Research Psychologist, USAF Aerospace Medical Research Laboratory, the technical monitor. We would also like to express our gratitude to Dr. Donald A. Topmiller, Chief, Systems Research Branch, Human Engineering Division, USAF Aerospace Medical Research Laboratory, Wright Patterson Air Force Base, and other personnel of AMRL who provided continuing intellectual support.

The actual research was accomplished through the diligent contributions of people associated both directly and indirectly with the project. Mr. Dan Riley and Ms. Laura Shaffer ran the subjects through the experimental procedures and analyzed the data in preliminary form, and Ms. Laura Shaffer also prepared the figures used in this report. Dr. George Ekel directed the analyses associated with one of the reports, and Ms. Linda Carlson-Wenger provided constructive criticism and prepared the manuscript through its revisions to this technical report.

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SECTION A

TR-79-2 An Information Processing Theory of Human Performance

Warren H. Teichner and Evelyn Williams

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AN INFORMATION PROCESSING THEORY OF HUMAN PERFORMANCE

Warren H. Teichner and Evelyn Williams

New Mexico State University

Introduction

This effort is an attempt to develop a theory about mental operations used by the human brain as it processes stimuli and selects responses to them. As such it is an exceedingly ambitious, and somewhat presumptuous undertaking considering the state of our knowledge in the area. On the other hand, it is one of a steadily increasing number of such efforts although admittedly most are of a less ambitious scope. In one sense, this theory is an attempt to integrate theoryies and models of lesser scope into a mutually compatible framework. As a result of the requirement for compatibility, as well as other considerations, some of our postulates and interpretations differ from current directions in the field. Some are novel; others are a reversion to previously discarded ideas and, still others reflect a change not in the postulate, but in the locus where the theoretical system operates.

For reasons which will be given shortly, we believe that the theoretical product of the experimental psychologist should be applicable to the "Real World" as well as to the laboratory. As a result, our efforts have been guided by the desire to formulate a theory of human performance which works in both places. The first part of the report briefly explains certain fundamental, not necessarily novel, ideas that we have about how a theory of this sort can meet the requirements for definition and test. The second part presents the theory first in an overall descriptive sense, and then in terms of the component stages of the theory. The third part attempts to provide research relevant to a more specific mathematical framework albeit incomplete and tentative with which to represent the theory.

We view this effort as a beginning, knowing that whatever we end up with will be seriously far from better efforts that will be available in the future. When we say that it is a beginning, we do not mean to imply that it is uninfluenced by other writers. In fact, just the opposite. However, since this is not an attempt to review the literature, we will not always give due credit to all of the sources of our proposals. For this we apologize, but with the observation that so many people are making so many theoretical proposals these days that tracking down the original source of ideas has become very difficult.

A theory of human performance is an abstract system from which we would predict task performance. That is, a theory of human performance is a theory of tasks. Our approach to theory is functional. We are concerned with the kinds of functions performed by the human brain doing a task. We are not to ignore what is known since that may place constraints on how we might conceive of the functions.

Teichner and Olson (1971) indicated that however a task is defined, it is always characterized by a transfer of information from an initial input to a final output. Whether one calls the stages which intervene between input and output <u>subtasks</u>, or <u>functions</u>, or <u>processes</u>, depends on the level of analysis of the system or task. This is true whether the system is a man, a machine, or a man-machine combination. A failure to understand the problems of levels analysis seems to be a source of undeserved criticism of some theories, particularly when expressed in the form of block diagrams. It seems also to be part of the source of failure of a considerable amount of theorizing effort. Some discussion of it is appropriate, therefore.

As we see it, the most important lack in human experimental psychology is the failure of psychologists to realize that what they are really talking about is human performance at tasks of some sort, and that that performance is always

partly dependent upon the operations performed upon equipment or some aspect of the environment. No measurement of human performance was ever obtained in a vacuum whether it be a measure of sensory function or the most complex thinking performance. Tasks, however, are selected or developed on a purely intuitive basis and with no rules for identifying communalities among them. By this we do not mean simply whether the task involved use of a keyboard or a television display, etc., although those enter into it. What we mean has to do with the specification of tasks in terms of the kinds of processing it requires. This lack of speicification of task properties in terms of information processing requirements creates problems for theory development. Theories are being developed whose generality is limited to the task used. They cannot be applied to other tasks simply because there is no way to identify the elements of other tasks as those related to the theory except by intuition and although intuition seems to be an accepted justification for many experimental and theoretical decisions these days, its use as an explicit or implicit justification reduces all that is done to its level.

It is a common practice to express the theoretical transmission of information through the human system in the form of probability trees, flow charts, block diagrams, signal flow graphs, etc. Such devices are especially useful for expressing transfer points, feedback relationships, and certain structural ideas such as serial and parallel processing. For the most part, when this is done, it has been to provide a graphic illustration of verbally developed ideas, or to describe a computer program as a functional model of the human system. It has not been used as a tool for manipulating theory. Whether it could be depends on the degree of mathematical development of the theory and the assumptions on which it is based. For example, a current issue concerns whether processing is carried our in a serial fashion so that all inputs travel the same

path, or whether the human system should be modeled as processing inputs simultaneously along different parallel paths. If the system could be conceived as a linear control system, a block diagram, or a signal flow graph, expression of the theory would permit certain algebraic manipulations. For example, in such a system the overall transfer function of processes in series is the product of the individual transfer functions, test of serial vs. parallel processing would be easy to make. In fact, a control theory approach to human performance is well-established and flourishing (e.g., Allen, Clement & Jex, 1970; Anderson, Connors & Pillow, 1971; Atkinson & Shiffrin, 1968; McRuer & Krendel, 1971). Its weakest element, unfortunately, is that concerned with the cognitive functions (Pew, Baron, Feehrer & Miller, 1977), and it is in those functions that we are particularly interested.

Perhaps the major difficulty with the application of control theory, or the development of any kind of information processing theory, is a complete absence of knowledge about probable feedback loops with the system. Surely such loops exist but our ignorance is so complete that even the most courageous theorist avoids speculation about them. As a result, information processing theories have not only been open-loop systems, for the most part they have been no-loop systems. We shall propose a theory which is closed-loop, and with some internal feedback looping. It is also a system in which stimulus processing and response processing go on in parallel. The theory lacks a great deal in sophistication, but perhaps it is a step in the right direction.

Consider a complex electronic system such as a computer or a television set which has developed a malfunction in a very small component. Now the system actually consists of a very large number of those components and other components wired together in highly complex ways with feedback loops, etc. Some years ago, finding the malfunction was a highly skilled activity requiring

endless patience in tracing circuits. Now, however, such systems are segmented into circuit cards each of which represents a logical function of the system. Circuit tracing is reduced to card testing. If the card as a whole indicates that it contains a malfunction within it, there is no need to find the malfunctioning component. To repair the system requires only replacing the whole card. Clearly, analysis of the system at the level of card function is a different level of analysis than at the more detailed component level. Similarly, it is possible to consider multiples of cards taken as single subsystems as functional units in which case the level of analysis is higher yet. At the highest or grossest level of analysis the system is a single input-output relationship. Description at this level is the simplest of all, but repair is so costly since the entire system would need to be replaced.

When the illustration is applied to a theory of human performance, small components and their complex wiring are analogous to details of the brain, but the analysis is incomplete since we cannot work either at the level of the detailed components, nor at the functional card level. What we attempt to do then is to construct hypothetical cards or functions, and to test those conceptions by predicting input-output relationships. Unfortunately, the level of prediction is not the level at which we construct our hypothetical functions, since we are restricted to the grossest, overall input-output relationships for our measurements. To be at all successful at such an enterprise requires operational definitions of our hypothetical constructs, i.e., a statement of which empirical variables are to be assigned as affecting which underlying functions, and what kinds of measurements operations and scales reflect particular functions.

That alone, however, is still not enough. We must be very careful about how we structure our underlying model for test purposes. For example, if we

have postulated two functions in series both of which are supposed to be sensitive to the same variables, and that sensitivity is reflected by the same response measures, we cannot test at all. In such a case, the problem may be handled by hypothesizing the joint or combined operation of the two functions and foregoing testing at the more detailed level. A different kind of example of the same principle applies to the situation where two functions are postulated as going on in parallel. In such cases, to test, it may be necessary to re-structure the entire conception to a grosser level where it may be treated as a serial phenomenon.

These issues will be considered again in context. For the moment, however, it should be noted that the meanings of certain terms depend upon the level of analysis or description. For the electronic systems mentioned, a card is an underlying process when the level of description is the single input-output relationship. The input-output relationship, itself, is a function. If, however, the analysis is at the level of cards, each card provides a function, and the underlying processes are at the component level. Also, if a task is defined as a transfer of information at a given level of analysis, then a function is a task; if more than one function is available in the description, each is a task. More conveniently, each is a subtask within the overall throughput, or overall task. Thus, functions are transfers of information whereas, processes operate upon information and, thereby determine what the transfers will be. It should be clear that what may be a function (or subtask) at one level of description may be a process at another.

It may be evident that a man is a system and that the system functions through communication links or subtasks. Regardless of whether the man is flying a plane or pushing a button, the <u>same system is involved</u>. To be sure, it appears to be a system which is able to couple effectively with a wide

variety of machines. But if anything is different from one man-machine system to another, it is not the man. It may be descriptively helpful sometimes to call one activity flying, another monitoring, another tracking, etc., but those terms should not be used to imply that different human systems exist in each case. The only human differences are in the degree of loading or activity of the human subtasks. A theory of human performance, therefore, must be a theory of subtask functions and processes. And the level of human system analysis required must be that which will permit an analysis of the performance of the human system at some desired level of control and accuracy.

Lest it be thought that concern with tasks is the sole business of the applied psychologist, we should point out what appears to be an increasing specialization among experimental psychologists with particular tasks. Some human experimental psychologists are simple-reaction-time-to-a-flash-of-light workers, some are letter-matching-same-different responding specialists, some are letter-digit visual searchers, some are immediate recallers, some are compensatory trackers, etc., etc. The logic of this specialization appears to evolve very simply. The investigator has a model of the processes associated with some major function of interest, perhaps attention, memory, etc. He develops or selects a task about which he will say that certain of its aspects are what he means by the terms of the model. Since the terms of the model are hypothetical and the aspects of the task are intuitive, he is in the interesting position when doing an experiment of not knowing whether he is testing his hypothesis or his intuition. In any case, if his results are agreeable to him, he accepts both as supported. Of course, another investigator with different intuitions may concentrate on another task and show that the first investigator's model does not fit <u>his</u> intuitions.

Our point is to emphasize that fundamental theorestical psychology is as direly in need of independent definitions of tasks or a task taxonomy as applied psychology. Experimental psychology is the psychology of task performance. So is applied psychology. The difference seems to be only in that the experimental psycholgist selects his task, whereas the applied psychologist has it given to him. A theory of human performance or information processing, or of cognition, or whatever else, then, should be equally applicable to both laboratory and "Real World" tasks. Our hope is that the present effort will make such a contribution.

The capacity of a machine system can be increased by replacing the limiting function with a higher capacity subtask, or by redesigning for parallel processing. The latter can be accomplished either within the system or by allocating part of the load to a second system. Since the human system is fixed, the only design recourse is to alter the task and/or add a second operator to share the processing load. But for a single individual, as noted, the maximum processing rate or capacity of the system can be no greater than the capacity of the limiting stage which is involved. Furthermore, in a single channel system, the capacity must decrease for every additional stage of processing involved. Thus, tasks which load fewer human functions than others can be done more quickly and with fewer opportunities for error and are by definition simpler.

The number of subtasks involved is just one form of complexity, functional complexity. Complexity may also be described in terms of the input code, the output code and the relationship between them, and that may be done at both the task and the subtask levels. Code complexity itself has two forms. One is based on the number of possible coded inputs and coded outputs, i.e., the number of possible messages in the signal or stimulus set and the number of actions or messages possible in the output or response set, message complexity.

The other form of code complexity is based upon the number of features or symbols within the stimulus and response messages, symbolic complexity. In all, therefore, we may describe tasks in terms of their functional complexity, message complexity, and symbolic complexity. Since the last two forms of complexity refer to the operations carried out within subtasks, they constitute the process or operational complexity of the task. However, else a task or system is described, regardless of the kind of system, its complexity resolves to a description of functional and process complexity. In turn, the processing rate of the system at any time is determined very importantly by those factors. It will become apparent later that process complexity can be manipulated with limits to compensate for functional complexity.

From the above it may be seen that tasks differ in terms of their functional complexity and in terms of operational or process characteristics. To say just that, however, or simply to invent functional and process characteristics has little value. The defining method must identify the functions and processes in an interrelated way within theory so that the theory can be used to predict or control task performance.

The General Theory

Teichner and Krebs (1974) divided their analysis of the one-to-one choice reaction time (CRT) paradigm between the development of empirical functions and a conceptual revision of Smith's (1968) formulation of Donders' Law. Donders (1969) proposed an analysis based upon subtraction of the selective reaction time from the CRT as a means for obtaining the time required for response selection in the CRT. The remaining time was then assumed to be due to all aspects of perceptual or stimulus processing plus the simple reaction time (RT), a constant which was also to be subtracted. The residual time was then supposed to be that required for stimulus processing. Aside from

whatever flaws may exist in these proposed definitions, they were a very meritorious effort if only that they attempted to provide operationally defined processing stages. As Smith (1968) has noted, CRT research since Donders has been guided by his basic notion (e.g., Sternberg, 1966; Briggs, 1974).

The results of Teichner and Krebs (1974) suggested that the RT component of Donders' Law may not be a constant, but instead that it may take up a significant portion of the time required for identifying the stimulus. Empirical support for that finding was provided by their own experimental data indicating that RT varies with stimulus information, and that it is longer for the mirror images of digits than for the normal view, and by the results of Bernstein, Schurman, and Forester (1967) who also found an increased RT with increased uncertainty in a signal detection task.

Generalizing the CRT formulation of Teichner and Krebs (1974) to all measures of performance (P):

$$P = f_1(a) + f_2(S\text{-}S) + f_3(S\text{-}R) + f_4(R\text{-}Sel) + f_5(R\text{-}Ex) \qquad (1)$$

where: $a = a_s + a_k + RT$ is that portion of the response measure, P, associated with stimulus encoding; a_k is a constant associated with a limiting neural transmission, and a_s is a stimulus encoding; S-S is the portion due to translations between stimulus codes; S-R the portion due to translation from the final stimulus code to the response code; R-Sel is the portion due to the selection of a motor program to carry out the action, and R-Ex was assumed to be a constant for a given, well-learned motor activity. Performance, P, is expressed as a measure of speed or error, or a combination such as amount of information transmitted.

The human processing system represented by Equation 1 is a serial system. Whether in fact the human is serial, parallel, or some combination of serial

and parallel processing undoubtedly depends upon the level of analysis employed. That is, if the stages (subtasks, functions) of Equation 1 were refined into more, smaller stages, parallel sybsystems might (or might not) emerge. At the level of analysis of Equation 1 serial transmission is indicated.

A task was defined as a transfer of information. Accordingly, Equation 1 describes performance on tasks for which all five subtasks are operative. Note that each subtask or function involves a transfer of information. Those operations which occur within the functions are the processes or operations which act upon the information and determine the amount or rate of its transfer.

Our task now is to achieve a more specific conceptual framework for Equation 1 by developing models to represent the processes on which the functions depend, to establish definitions and measurement concepts to describe the behavior of its process and functions, and to develop interrelationships or transfer functions between subtasks. We start that by expanding the level of description to account more specifically for perceptual and motor phenomena. Then, we shall consider each of the component functions in turn with proposals for models of the underlying processes.

First, we shall consider a block diagram of the portion of Equation 1 which is the stimulus processing system. Then we shall expand the motor system functions indicated. Finally, the two will be combined into one system. In doing this our emphasis will be on general explanation of subtask functions with minimal appeal to empirical support. Relevant empirical data for this and other components of the model will be presented at the end of the theoretical description. And in order to enhance our explanations, we shall try to relate the concepts loosely to specific simple examples and laboratory tasks.

Up through f_3, Equation 1 may be expressed as shown in Figure 1a, except that one more process, the short-term storage of information (STS), has been

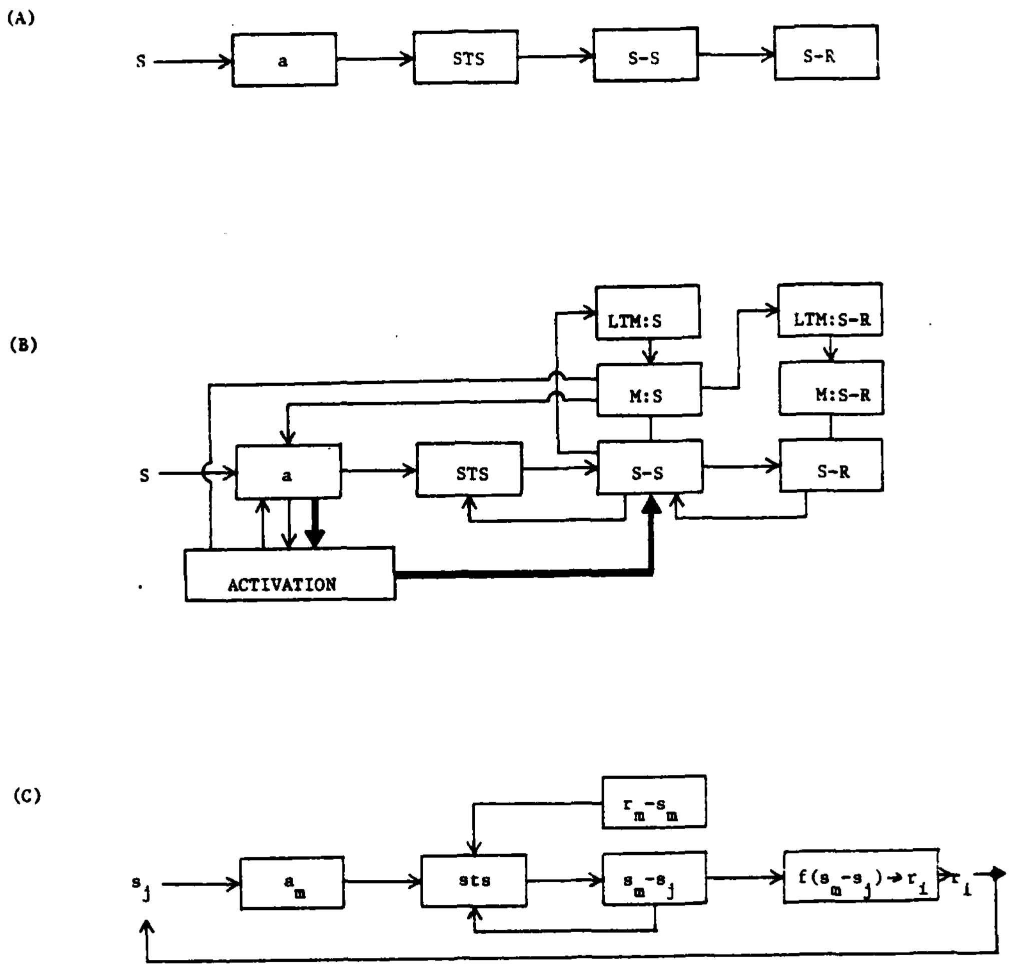


Figure 1. Block Diagram I: Human Performance Theory.

added. In this figure, S represents energy changes in the internal or external environment which impinge upon the receptors of the organism. The stimuli involved in the processing are symbolic stimuli (Teichner & Olson, 1971) which means that they are identifiable by the individual in some way when they are at sufficient energy. Other, non-symbolic, stimuli do not usually reach sufficiently high energy levels to be identifiable by the individual. Nevertheless, they may be effective stimuli operating through systems about which the individual usually has no awareness. The system of particular interest concerns those stimuli which are proprioceptive signals from the actions of muscles and joints.

From the receptor, the stimulus is transmitted to the a-function where a decision is somehow made about whether it is a stimulus which will receive further processing. If the decision is to continue processing, the stimulus, now encoded or identified to some degree, is transferred to a short-term storage (STS) where it is available for further processing. In Figure 1a these postulated events are included in the a-function and the STS. We shall also assign to the a-function decisions about signal duration and about the temporal order of successive stimuli. Consequently, the a-function depends on at least two central processes: (1) a response decision process, and (2) a temporal processor.

While the signal is available in STS, it is assumed to be transformed from whatever coded form it is in to a new stimulus code <u>if necessary</u>. For a crude example we might suppose that S is a sound which is to be identified as a word in a recently-learned foreign language. Suppose the word is "alto." While it is in some equivalent of a sound form in STS, it may be translated (1) from the sound to "alto," and then (2) from "alto" to "stop." These are two S-S translations. Now that it is translated to "stop," a response must be selected

as a reaction to it. For an individual driving a car, the response might have something to do with applying a foot to the brake. Selection of that response is accomplished by the S-R translation. That is, S-R translation is a translation from a stimulus code to a response code.

The example just given concerned someone to whom Spanish was a new language. For the person for whom Spanish is the native tongue, or for the very fluent person for whom it is a second language, the second S-S translation is assumed to be absent. That is, for many tasks, S-S translations which are required through some portion of learning of a task may drop out after that portion. We may postulate also for relatively simple tasks which are very well-learned that S-R translations may also be reduced in complexity or number. Thus, with learning, tasks tend to become less complex through the loss of subtasks.

A number of writers have described a postulated loss of intervening function and its associated increase in speed of performance as the development of automaticity in performing (e.g., LaBerge, 1975; Shiffrin & Schneider, 1977). This is a very unfortunate and misleading use of the term. With loss of function of the sort indicated, the task becomes simpler (by our definition). Aside from that, it should become less variable in its measures of performance since there are fewer functions to contribute to the variability. It should require less time since fewer functions are involved which require processing time, and the error rate should be less since there are fewer sources of error. None of these imply automaticity which in its more general technical usage has to do with self-regulated processes. That is, the greater the amount of self-control of a system, or more specifically, the greater the number of feedback loops, the more automatic the system is said to be. Thus, an increase in automaticity implies an increase, rather than a decrease in the number of

internal relationships. As the number of those (feedback) relationships decreases, the system becomes less automatic and more under control of external forces. It becomes less of a closed-loop and more like an open-loop system. In these terms, the loss of functions with learning is just the opposite of automaticity. And, as in the case of control systems, as those functions are lost, the individual comes more and more under the direct control of the stimulus. If any term is appropriate to this it is stereotypy.

Figure 1b provides postulated functions which control the functions shown in Figure 1a, or which operate interdependently. Of initial interest are two more or less permanent or long-term memories. One is a memory for stimuli, LTM:S. This memory contains a storage of names, sensations, synonyms, autonyms, images, or, in general, all of the stimulus events which have been experienced sufficiently to remain stored. It is a dictionary, encyclopedia, set of maps, classifications, rules, and any other systematic organization of stimulus events. We shall make no attempt to consider possible subclasses of memory such as acoustic, visual, semantic, etc. If a multiplicity of memories exist, they are the processes underlying our single memory function.

We postulate that the LTM:S function includes the ability to search, locate and organize information in its contents into subsets the elements of which and their interrelationships represent stimulus events which have been experienced as present with a particular kind or specific instance of overall task. Some of these stimuli are relevant to the task which means that the probability of a response to them required by the task is greater than zero. Some of the stimuli are irrelevant, which means that the required response should be independent of them. As shown in Figure 1b, M:S is a subset of LTM:S; it is an active working memory (Baddely & Hitch, 1974, 1977; Sternberg, 1966).

What the working memory will contain is determined by experience with the task. The event which directs the operation to a particular subset is an instructional stimulus. That could be a verbal statement or some other stimulus event which is different from the events in the available working memory. Figure 1b shows, as before, that stimuli are transferred to STS and then an S-S translation occurs. The translation is now seen to be an operation performed within the working memory as a comparison with what is in STS. If the translation is not possible because the stimulus in STS is not one of the subset, the operation within the working memory is assumed to be halted and the contents of STS inspected to verify the signal. Two possible things might have happened. The stimulus transferred to STS was one of the subset, but was distorted while held in STS. In that case, it might be verified as a proper signal and the S-S translation would be resumed. Secondly, it might not be verified, either because it was distorted beyond verification, or because it was not found in the set. In either of these two cases, we assume that the system will treat the signal as an instruction to develop a new working memory based upon what characteristics for identification are available in the stimulus. The actual command to do that is shown in Figure 1a as the line from S-S to LTM:S. Note that this loop also accounts for the effects of novel and unexpected threatening signals.

The loop between S-S and STS represents two other achievements of the system based on the same processes. In general, the return signal represents inspections of STS. That may occur for a number of reasons. First, assuming the comparison process within M:S is accomplished through a matching of stimulus features, the loop represents a successive extraction of those features and successive comparisons. We would expect, then, that the more critical features involved, the longer time needed to decide if the stimulus is in the subset.

We assume too that under all cases of doubt about the signal or failure to find it in the subset, STS is reinspected at least once.

The second accomplishment of the loop is that after a stimulus has been compared, the system is able to process another one. Thus, completion of the S-S comparison is signalled by the return loop to STS and a new stimulus is retrieved from STS for a new comparison.

The S-R translation also depends upon a learned long-term storage. In this case, it is a storage of S-R relationships. It is assumed that a working memory can be established for a task which consists of S-R relationships associated with the task once the appropriate subset of stimulus events has been identified. Note that the S-R relationships in the subset must be those which involve the stimulus in whatever form it is encoded <u>after</u> S-S translation. Conversely, stimulus representation in the a-function must be in the same form as the <u>first</u> or untransformed S in the S-S translation.

To take a simple example, assume an individual carrying out an accustomed task in a normally quiet room who suddenly hears a very loud sound. The sound stimulus would be processed into STS and a search for it in the working subset conducted. Since it would not be found there, STS would be re-inspected and it would be processed in M:S another time. If again, it failed to match an element of the subset, the S-S operation might stop and a signal would be sent to LTM:S. That would constitute an instruction to LTM:S to identify a class of stimuli for it, and to establish a new working memory. In turn, a new working S-R memory would be established. One result would be a delay or halting of the stimulus processing, and a consequent delayed response.

Suppose that no identification could be made of the sound. In that case, the working memory might contain a set of alarm signals and the S-R memory might contain responses equivalent to "freezing," orienting, running, etc.

If the stimulus were persistent, identification might be possible. If it were not, the system might wait for that period of time required for it to have dissipated in STS and then re-establish the initial working memories. During that time task signals might have been stacking up in STS, and if the time were long enough, some of them would also have dissipated. Related phenomena to be discussed in terms of the particular functions concern habituation to stimuli, and the fact that more than one response may develop to a given stimulus.

Figure 1b also shows an activation function. We assume that the general level of activation required for a desired level of performance is a state that is identified with learning of the task. That level is associated with the M:S. Thus, the figure shows control of the activation mechanism as an information transfer from M:S. It is assumed that the activation mechanism exerts a control of the processing within the a-function, and in turn, events within that subtask stimulate the mechanism so that the activation level is maintained. Should the frequency of input to the a-function decrease from expected levels, therefore, the activation level would decrease with a consequent effect on processing within the a-function. This relationship is shown by the heavy line indicating a second transfer of information from the a-function to the activation mechanism. An effect of that relationship other than the one just noted, is an increase in activation level associated with alarm stimuli. Novel stimulation, on the other hand, cannot be activating until they cannot be identified in the S_1-S_1 translation. Thus, it can be predicted that defensive reactions should be made more quickly to alarm than to novel stimuli.

Figure 1b also shows that the activation mechanisms also control S-S translations. The control that is effected is of the translation rate. Under normal task conditions, the rate determined is associated with previous experience, so that an S-S rate is a necessary consequence of the establishment of a particular M:S.

Whereas Figure 1b is a symbolic stimulus processing channel, Figure 1c represents the processing of proprioceptive stimuli associated with motor activities. It is therefore a motor processing channel. However, since only stimuli are processed as information, responses being selected by association, it is really also a second stimulus processing channel. Consequently, we have structured it in a manner comparable to the symbolic stimulus channel with the exception that additional long-term memories have not been postulated.

Consider an individual who has just completed pressing a button on a key-board in response to a signal. The next signal will require him to press a different button. If the signals occur randomly, he has no way to anticipate a sequence of button press responses. Suppose now that the actual sequence of motor activities required to move his finger from its present button position to the next one consists of a: (1) finger lift, (2) finger aim, (3) finger move a fixed distance, (4) finger down to contact, and (5) finger apply force. Of course, these steps overly simplify in that they ignore movement rate and represent arbitrary segments of the total motor act. Accepting them, though, the only new information supplied by the new signal concerns aiming and distance. The other segments are identical for all button press responses.

Since these are motor segments of a total action which is called a response (R), we shall identify each segment as r_i. Each r_i has a consequent stimulus event which may be designated s_i, or to show the necessary relationship, r_i-s_i. In fact, however, each of the five segments of R also consist of a sequence of motor events, e.g., the selection of muscles and required contractions and relaxations, the ennervation of muscles, etc. Thus, finger lifting is really more accurately described as a sequence of motor activities, $r_1 - s_. - r_2 - s_2 \ldots r_n - s_n$, where r_n is the final motor act associated with accomplishment of the sequence. Then each of the five segments may be identified as $r_{n1} - s_{n1}$, $r_{n2} - s_{n2}$, $\ldots r_{n5} - s_{n5}$.

Now suppose that somehow an instruction were given to the channel to perform the first segment, a finger lift. There would already be in the channel signals resulting from the last motor activity. This is represented in Figure 1c as s_j. It may be seen that that signal is processed by a_m which is an initial processing subtask for motor-produced stimuli comparable to the a-function, but with different parametric values. It is then transferred to a short-term (motor) storage (sts). At this point the two channels differ because it is assumed that the instruction, $r_{n1} - s_{n1}$ is available in sts at the same time. The s-s operation conducted is not one which employs a working memory, but one which determines the difference(s) between s_n, the desired stimulus event, and s_j, the actual one. The subsequent s-r translation performed is one which makes necessary computations to derive an r which will correct that stimulus difference. In turn, that r generates an s which is compared to s_{n1}, and again until the difference is acceptably close to zero. When that happens, the finger is lifted, and the channel is ready to evaluate $r_{n2} - s_{n2}$ in the same manner, etc. until the final $r_n - s_n$ has been achieved, that is the new button response has been made.

Actually, the example used is of a case which is generally trivial, although it becomes less so as the keyboard becomes larger. It is trivial because for a fairly small keyboard, the times required for each of the motor events in the sequence are very small and with practice, become essentially constant regardless of direction and extent of movement. The example, neverthelesss, as an easy introduction to more complex kinds of motor activity.

Figure 2 combines the two channels into one system. All of the elements previously discussed are present. Now, however, it may be seen that the instruction to the motor channel is the response arrived at as an S-R translation. R is the sequence of motor events and the consequent stimuli required to produce

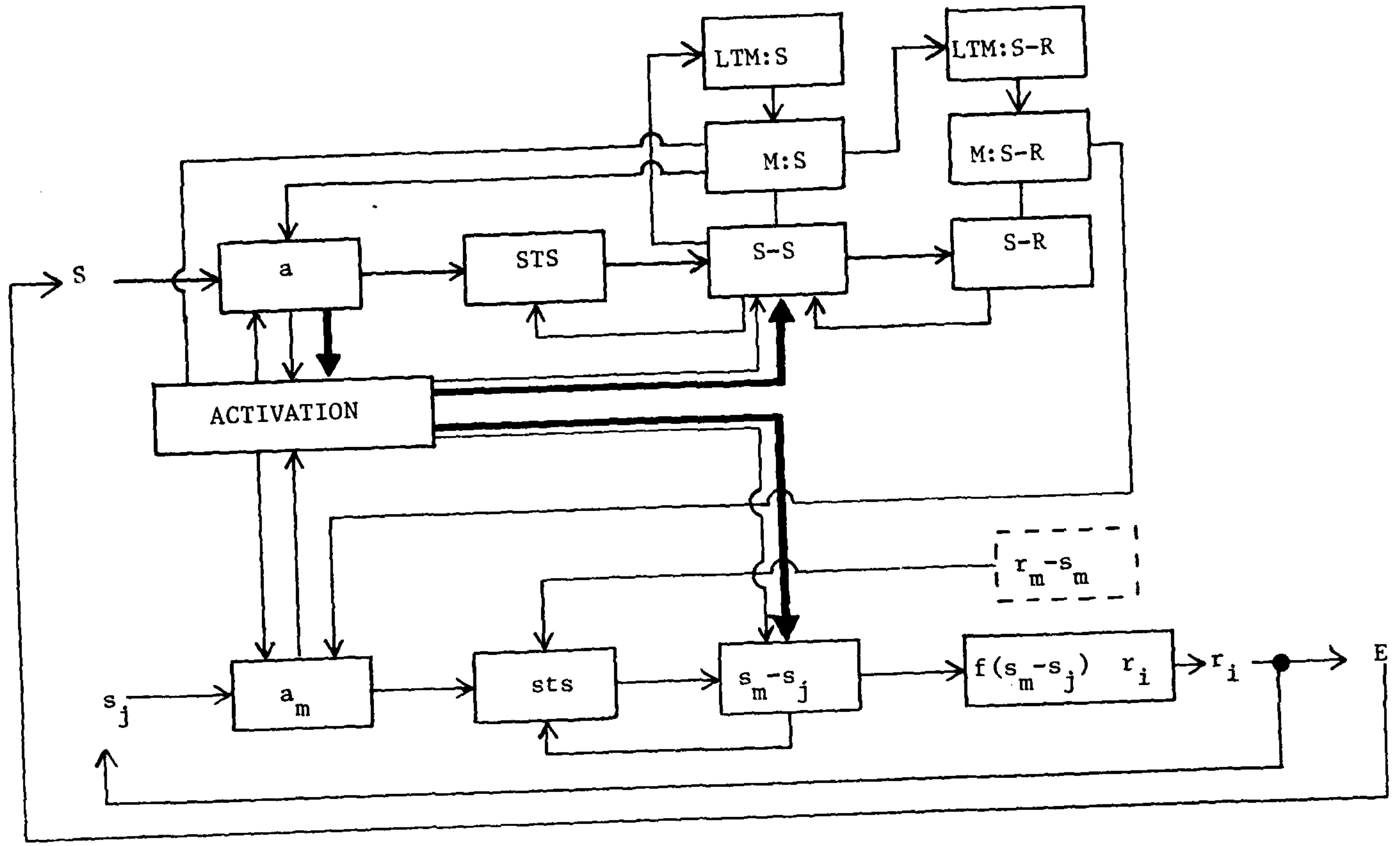


Figure 2. Block Diagram II: Human Performance Theory

a given effect on the environment (E). The motor code into which S is translated is the language of the motor channel. It may also be seen that M:S-R is assumed to establish the processing characteristics of a_m just as M:S does of a, and that the relationship between the activation mechanism and a_m is comparable to that of the a-function except that no special increase in activation is allowed. Finally, it may be seen that changes in E produce new symbolic stimuli. We may anticipate then that S-S operations are possible which also produce difference or error values which can result in the instruction to the motor channel being a deviation or error.

Figure 2 presents two channels of information processing which go on in time parallel. Within each channel we assume serial processing at the level of analysis indicated. That does not mean that processes within the subtasks cannot go on in parallel.

The a-Function

Perhaps the oldest problem in psychology concerns the selective nature of behavior (Sanders, 1963). People do not respond as if to every stimulus in the environment. Is it, therefore, that selectivity is accomplished by placing constraints upon <u>which</u> stimuli will be processed, or <u>how</u> they will be processed? Or is it that all stimuli are processed without differential treatment, but constraints are placed later which affect to which stimuli responses are made? Perhaps both kinds of constraints operate. These possibilities define the scope of theoretical interest in the problem of attention as formulated since Broadbent (1958) reintroduced it into psychology. It is a scope which is clearly beyond fair treatment here. Therefore, we shall deal with it only to the degree needed to explain how the present theoretical approach handles the problem of selectivity. Excellent discussions are available (e.g., Broadbent, 1971; Egeth, 1967; Moray, 1969; Smith, 1974; Treisman, 1969).

The a-function provides decisions about sensory events which determine the probability that a stimulus input will be processed further, which establish the apparent duration of stimuli, and which determine the apparent temporal order of stimuli. Although these decisions are predetermined by requirements established in the S-S subsystem, and are also subject to arousal effects, they provide a basis for the selective nature of behavioral phenomena. They also contribute to phenomena which are usually considered to be essentially sensory in nature. The a-function stands as the transition between peripheral and central processing to the degree that it is reasonable to think of processing in the nervous system as bipartite.

Information must be on hand to be processed. As a consequence, to model an information processing system requires devising a way for the information to be present when the processing operations occur. Another problem concerns the nature of the data to be processed in order to develop an appropriate data processor. Neisser (1967) proposed a sensory store, or icon, as a stimulus buffer on which "preattentive" processes operate. Sperling (1960) provided a clear demonstration of the presence of informational items in the system which are normally unreported in immediate free recall. Sperling's interpretation of his data, as well as later studies (e.g., Averbach & Coriell, 1961; Sakitt, 1976; Sperling, 1963, 1967) have led to considerable agreement about the existence of an icon as Neisser suggested, although there have been objections (Gardner, 1973; Holding, 1975; Melton, 1963). Theoretical presentations of cognitive processes now usually start with a description of a sensory register or icon as a very short duration, unlimited-capacity representation of events as they are present on the receptor organ.

There are difficulties with that concept of the icon. First of all, if what it represents is merely a one-to-one representation of events at the

sensory organ, it has no theoretical value. The sensory organ provides a sufficient description. Such an icon is redundant, and even if it does exist, we do not need to know about it to model the system. In fact, a completely redundant stimulus buffer is what is generally proposed.

However, considering the retina as an example, stimuli at different retinal locations appear to vary in speed of neural transmission, and stimuli of different intensities seem to vary in their post-retinal persistence. We shall consider these important factors again shortly. For the moment, however, what is implied is that the sensory register need not be simply a redundant replica of the sensory organ. In fact, what it may contain are representations of stimuli as well as aspects of stimuli which differ from those on the retina because of the temporal parameters involved in post-retinal processing. On this ground the concept is useful. That is, the icon is not merely a very short-duration stimulus storage, but it is the actual or proximal stimulus at any moment and that could differ considerably from a one-to-one representation of events at the sensory organ. We would expect that many of the illusory aspects of perception could be explained by a detailing of the sensory register at any instant as the proximal stimulus.

Therefore, we do postulate the presence of a rapidly changing sensory register which reflects what is available at the sense organ conditioned by post-receptor signal processing. Specifically, we assume that the greater the energy in the stimulus, the faster is the transmission to the sensory register. This assumption has a good physiological basis. We shall also assume that the greater the energy in the stimulus, the shorter its persistence on the icon. This assumption is not well-established, but there are suggestions to support it (Efron, 1973; Engel, 1970; Piéron, 1939). These assumptions imply for vision that luminance, area, and duration within limits will determine transmission

speeds and signal persistences, and that their effects as energy variables are completed before central processing begins. At the same time, are contributes to a location code, luminance to a brightness code and, within limits, duration determines how long the signal will persist without removing it and restimulating (as with eye movements).

At some point a decision is made about each stimulus as to whether it should be given further processing. That decision depends upon information which is not in the stimulus as such, but which depends upon previous experience with it. That point, where a decision based upon previously acquired information is made, is where we shall consider central processing as starting. We view that as what happens in the _a_-function; the icon is assumed to be the last stage of peripheral processing.

We shall develop a two-stage model of the _a_-function. One stage provides a sensory decision to the other which then provides a temporal decision. Signals which pass through both stages are retained in STS. Each stage of the model will be considered separately in the following discussion. They will then be brought together and new data employed to evaluate them.

As shown in Figure 2b, an active working or operating stimulus memory, M:S, is available prior to any trial on a task. That memory is assumed to contain representations of those stimuli which have been learned to be relevant to the task as well as those which have been learned to be irrelevant. These stimuli, then are those that are expected to occur on any trial with one or another expectations of occurrence. All of these stimuli are also somehow represented in the _a_-function. As the working memory changes, the _a_-function changes.

Also contained within M:S are representations of two other classes of stimuli. One of these is of stimuli that are very importantly involved in so

many task activities that they are generalized to all tasks unless special training is given to eliminate them. A particularly important example for the normal adult concerns the printed or spoken word. It is assumed that language stimuli are generalized to all tasks for such people. Adult illiterates or young children would not be expected to have visual stimuli of this sort in the set, but they would be expected to have auditory language stimuli present. When such stimuli are irrelevant, they may interfere with performance although how they do that is a question for later. Conversely, an individual who spends a great deal of time at a specific kind of task, would have other kinds of irrelevant stimuli in his relevant set, and he might have currently relevant stimuli in his irrelevant set until he has overcome prior task learning with sufficient practice. The degree to which the relevant and irrelevant sets are the same for any two tasks partly determines the transfer of training between them.

The third set of stimuli in the working memory is alarm stimuli. What these may be is hard to specify. They may range from the odor of smoke, or reflect pain, or represent intense lights or sounds or simply one's name. Regardless of what they are, they are always present and the individual always has a quick readiness to respond to them. In particular tasks with unusual alarm requirements the task-specific alarm stimuli will normally be part of the relevant stimulus set. However, if the tasks which involve those stimuli occur frequently enough, those stimuli may become part of the alarm set. We can conceive of a soldier in a combat zone developing an alarm set which contains stimuli that he was originally taught to view as relevant. Conversely, some stimuli which function initially as alarm stimuli become habituated, that is, with experience they become part of the irrelevant set.

The form in which we shall represent the stimulus sets in the a-function is a variable response criterion model developed by Grice (1968). This is a

form of counting model, and because it is a counting model, it is very attractive for a number of reasons. One of those reasons is that it permits dealing with both latencies and the frequencies of events separately and combined into more complex measures. All such models are statistical decision models and in that sense, they are in the class of the theory of signal detection. Unlike that theory, however, they need not make assumptions about maximum likelihood as a decision criterion, nor is it necessary to assume that signals are always embedded in noise.

Counting models of psychophysical events and of reaction times have been of increasing interest and have been developed with a reasonable degree of success when applied to simple latency problems and psychophysical probabilities (e.g., McGill, 1963; Luce & Green, 1972; Pike, 1973). Most of these models assume random variation in the stimulus or neural event, frequently in terms of a Poisson distribution, and a fixed decision criterion in the individual. In a mathematical sense it makes little difference where the variation is assumed to be, but in terms of further explication of the characteristics of the individual and the interdependence between this early portion of the information processing and later, it makes a great deal of difference. Grice's model, therefore, is especially attractive because variation does reside in the individual. Furthermore, Grice has developed his model empirically to the point where it appears to be applicable to a wide variety of situations.

A physiologically well-established assumption of the model (and all counting models) is that neural events which follow stimulation can be represented as pulses. It is then assumed that when a criterion number of pulses or amount of "evidence" has been accumulated, the response will be initiated (or here that further processing will be initiated). What we mean by "evidence" will be discussed later in detail.

The basic ideas of the model are illustrated in Figure 3. The ordinate of Figure 3a represents a cumulation of pulses of evidence about the stimulus following stimulus onset. The solid horizontal line represents a response criterion (RC). The abscissa provides time since onset of the stimulus or latency of the process. A lag is indicated to account for a delay which we shall ignore for the remainder of this explanation, but which is the sum of efferent transmission and the peripheral processing. Line A represents the accumulation of stimulus evidence over time. It is clear that it would take longer to reach a higher RC than the one shown. Furthermore, the higher the RC, the more evidence available about the stimulus, and, therefore, the less probable the processing error. Thus, the RC model has a built-in speed-accuracy trade-off.

Line A represents a relatively intense stimulus; Line B represents a less intense stimulus. The rate of pulsing or of evidence accumulation is assumed to increase with stimulus intensity, and that is represented by the slopes of the lines. Line A reaches RC sooner than B and consequently is associated with a smaller latency even though the two stimuli were initiated at the same time. Direct evidence for this aspect of the model is provided by Teichner and Krebs (1972) who showed over a variety of studies in the literature that the simple reaction time to a flash of light is a decreasing, negatively accelerated function of total stimulus energy. Thus, if RC is constant, Equation 1 represents a reciprocity between luminance and RT which would be expected from Figure 3a.

Line C of Figure 3a represents an even more intense stimulus than A, but one which was initiated at some time after A. Because it has a sufficiently greater slope, it actually reaches RC sooner even though A was initiated first. We would expect, then, that if both stimuli were presented in succession,

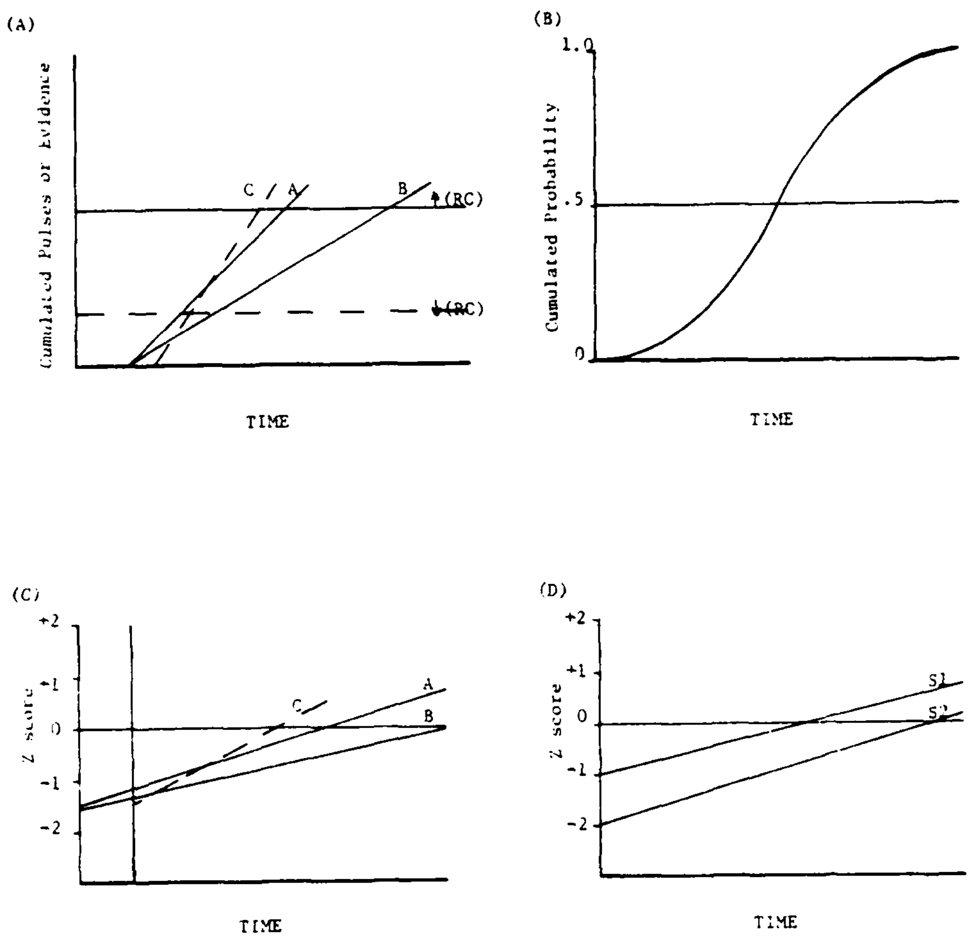


Figure 3. Response Criterion Model

response would be made first to C, ignoring other very important considerations to be discussed below. Not though, that for a very low criterion level such as the dashed line in Figure 3a, Line A would have reached criterion first. Expectations of this sort are supported by temporal order judgments. For example, Rutschmann (1973) demonstrated that the visual temporal order judgment, which of two stimuli come first, depends on the relative intensities of the two stimuli, and Corso (1976) reported a similar finding for the comparable auditory judgment.

The RCs are postulated to be distributed normally. We shall assume that variation occurs from moment-to-moment, or more realistically, from trial-to-trial. Figure 3b indicates that the mean RC is that value of the stimulus evidence which will elicit a response with a probability of $p = 0.5$. The transformation of such a curve to normal deviates yields a linear function as shown in Figure 3c. The three lines of Figure 3a are shown in Figure 3c with a second ordinate drawn in for clarity. As before, the slopes of the lines reflect stimulus intensity.

Figure 3d presents the case for two stimuli of equal intensity, but wiht different RCs. The RCs are expressed as the y intercepts of the lines. As shown, each criterion will vary normally, and since the disturbances are overlapping, each one will reach criterion before the other a certain proportion of the time. If stimulus S_1, the stimulus with the higher RC (larger negative number), were in the irrelevant M:S set, it would still be processed before the other stimulus, S_2, a certain proportion of the time.

Figure 3d is the form in which we will use the model. It is worth noting that the model is Thurstone's model for absolute scaling (1925). Its similarity to the theory of signal detection has been noted by Grice (1968). The present form of the model is based primarily on a solution proposed by Diederick,

Messick and Tucker (1955), revised in Torgerson (1958). We shall not in this paper take advantage of all of the possibilities for scaling inherent in the model. For those interested, however, Grice (1968, 1977) should be consulted.

Of particular interest for present purposes is the use of the cumulative latency distribution illustrated in Figure 3. The values of this distribution may be viewed as an index of the average amount of information processed. This depends upon the rate of processing and the parameters of the criterion distribution. Thus, the normal deviate for any given probability reflects the information processed in the corresponding time. As shown, the measure is taken from the mean of the crtierion distribution ($z = 0$) on a scale with σ as the unit. To express this differently, for distributions such as in Figures 3c and 3d, the relationship between z and t is linear with slope $A = 1/\sigma$, and intercept, $k = A\overline{X}_t$. This is a least-squares solution of the function,

$$z = A\overline{X} + k \tag{2}$$

where z is the normal deviate, A is the slope of the function, and k is the intercept as demonstrated by Diederick, Messick and Tucker (1955). Accordingly, A reflects the rate of processing and k reflects the RC. The model is especially useful in comparing the effects of different stimulus conditions on common scales as well as determining whether different effects were due to a difference in criterion, or processing rate, or both. In addition, as Grice (e.g., Grice, Nullmeyer & Spiker, 1977) has demonstrated so well, the scaling properties of the model may be used to derive functions for underlying hypothetical processes.

Whereas, the cumulative normal distribution may be used to derive an index of information transmitted, as Grice has also shown the cumulated latency distribution may also be used to determine the stimulus uncertainty reduced, or actual stimulus information transmitted up to any point in time. That is,

using the proportional distribution of response in any time interval as a source of response information, the information transmitted in that interval can be determined. Similarly, using the cumulative amount of information, up to and including that interval, represents the cumulated amount of information processed up to and including that interval of time.

The temporal parameters of the hypothetical neural event are necessarily critical to the model. Although available counting models appear to assume that all stimuli have the same persistence, as noted above, we believe that the evidence available is beginning to suggest that the greater the intensity of the stimulus, the shorter its persistence (Efron, 1973; Engle, 1970; Pieron, 1939). Assuming that, it is clear that an RC could be set sufficiently high that the amount of evidence accumulated in the period after stimulation would never reach criterion. Thus, while all stimuli may be processed to the a-function, not all stimuli may be processed beyond that point. On the other hand, it is reasonable to expect that most of the stimuli for which a criterion that high might be established are likely to be very frequently appearing irrelevant stimuli. Note that this assumption of an inverse relationship between intensity and persistence, is not a necessary assumption for the expectation that a stimulus would be lost before reaching criterion if the criterion were high enough. It is well-established that even a constantly-present physical stimulus produces neural impulses which increase in frequencey and then recover to baseline as the stimulation continues, and, as with the stabilized retinal image, that the stimulus fades out even with a continued retinal presence.

The criterion level for any stimulus has been shown to depend upon learning and/or cognitive variables (Grice, 1968, 1977). Accordingly, we assume that RC is subject to alteration by motivational factors, payoff values, and degree

of experience with the task, and that the actual level established is determined by the influence of those variables in the M:S. Early in the learning of a task, it is likely that the RC levels for most stimuli will be low. With continued experience, the RCs of irrelevant stimuli will become higher and those for relevant stimuli will tend to reflect probabilities of occurrence, payoff, and other decision factors. Note that the risk of being wrong could be such that an individual could establish such a high RC that the stimulus would fail to reach it.

As shown in Figure 2b, the control of these RCs is accomplished by instructions or commands from M:S to the a-function directly, and from M:S to the activating mechanisms, and thence to the RCs. The direct control represents the learned effects of decision variables. However, the RC level is also assumed to be influenced by activation through M:S-activation control, and this too represents the effects of learning. In this case, it is the learning of an optimal activational level for the task situation. Other influences such as the effects of arousal will also affect the RC level in addition to that established indirectly by the LTM:S control. The relationship is assumed to be inverse, at least to some limit after which it may reverse itself, in accordance with the Yerkes-Dodson law (1908) and other expressions of bodily arousal. That is, as arousal increases, RC decreases, and then increases. This leads to the prediction that as the arousal level increases, latencies should decrease, but errors and false alarms when possible, should increase.

The effect of arousal on the RC also accounts for the usually understood finding for infrequently appearing signals in watchkeeping tasks that the probability of detecting the signal decreases with duration of watch (Teichner, 1974). That phenomenon can be explained as a decreased arousal level which in turn produces an increased RC, and if sufficiently high, an increased probability

of missing signals. In fact, Teichner (1974) has shown that the latencies of detection responses in such situations are consistent with the other expectation; that is, that as the probability of detection decreases, the latencies increase.

Finally, regarding the RC model, it is assumed, for reasons that will become apparent in the following section, that the rate of processing of the stimulus evidence to the criterion depends <u>only</u> on stimulus energy factors, i.e., on peripheral processing. It cannot be adjusted by later processing requirements, and it is independent of activation. In any actual experiment, however, recognizing that all we can measure is a stimulus-response relationship, the obtained processing rate may reflect the effects of this primary processing rate plus the effects of processing later in the system. Then, the maximum processing rate that can be achieved is that which reflects only the *a-function as nearly as possible. One way* to evaluate the contribution of a function later in the system is to compare the processing rate obtained with that function assumed to be added to the processing burden.

Timing

Two stimuli presented one-after-the-other can be discriminated as non-simultaneous unless the time difference between them is less than a critical amount. In that case, they <u>may</u> be seen as simultaneous. Our present concern is with how that is accomplished, and with the related question of the manner by which the duration of an event is judged. Is there a central process which resolves the differences; are those differences resolved peripherally, or both? The possibility of a central resolution of time is of great interest because the mechanism involved may provide a unit of psychological time on the basis of which durations are estimated and information processing is limited.

Hirsch and Sherrick (1961) make an important distinction between temporal acuity, the minimum interstimulus interval (ISI) required to distinguish that two stimuli are successive rather than simultaneous, and temporal order resolution, the minimal time required to determine which of the two stimuli came first. In a now classic investigation, they reported that temporal acuity requires a smaller ISI than order, that acuity varies with the characteristics of the sense modality, but that temporal order has a 75% threshold of 18-20 msec ISI regardless of sense modality (vision, hearing, touch). From this they concluded that acuity is a peripheral phenomenon, but that order depends upon a single central temporal processor common to all of the senses.

In a series of studies since then, Rutschmann (e.g., Rutschmann, 1973) has shown that the temporal order threshold depends importantly on the characteristics of the stimuli used and, for intramodality stimulation, on receptor characteristics. For example, she reports different thresholds of order for two stimuli separated by different distances on the retina, or which vary in luminance. Such findings, however, seem to require accounting for the opportunity provided by intramodality differences for uncontrolled variations in the speed of neural transmission and for the use of non-temporal cues by the subject. Thus, even though Hirsch and Sherrick's actual data may be questioned in part because they did employ stimuli at different retinal distances, their fundamental conclusion appears to stand. Evidence supporting the concept of central temporal processing since Hirsch and Sherrick has accumulated steadily (e.g., Allan & Kristofferson, 1974; Babkoff, 1975; Corwin & Boynton, 1968; Effron, 1963, 1973, 1974; Kristofferson, 1967a, 1967b). Detailed reviews and analyses favoring a central mechanism have been provided by Sternberg and Knoll (1973), Stroud (1955), and White (1963) among others.

Sternberg and Knoll (1973) suggest that to avoid confounding by peripheral stimulus-receptor factors each of the two judged stimuli should be presented along a different sensory channel, e.g., a flash of light and a tone separated by an experimental temporal interval. Unfortunately, this is not without receptor complications either since it requires the unlikely assumption that the intensities of the two stimuli are somehow equal, and, therefore, that their arrival times at the central processor are under experimental control.

On this basis their proposal to employ the point of subjective simultaneity for intermodality comparisons is no less a confounding of neural transmission times and relative intensities than is the case of two stimuli at different points on the retina.

A partial solution, exemplified by Kristofferson's work with intermodality stimuli, is to take account of the sign of the successiveness differences at the successiveness threshold (Kristofferson, 1967a). In this way, even though the intensities are not equated, at least their relative levels can be inferred. The point is that using stimuli from different senses does not uncomplicate the problem produced by using stimuli within a modality. If anything, it makes the problem more difficult because stimulus intensities can be compared and equated intensively within, but not between senses. Matin and Bowen (1976) have proposed a way to calibrate arrival times using the point of subjective simultaneity as a criterion. This alone does not solve the present problem since we cannot both calibrate and then conlude about temporal order with the same criterion. However, we could first calibrate intensities by actual simultaneity, and then test for non-simultaneity or for which came first at varying temporal intervals.

We conclude that appropriately controlled stimulation at two different locations on the retina could be an acceptable method for the study of temporal

resolution provided that non-temporal cues associated with such a method are not employed either in addition to the temporal characteristics of the stimuli, or instead of them, and providing that the differences in transmission times are compensated by differences in intensity. One of the available cues is an experience of apparent motion which is available to the subject to use either instead of or in addition to temporal factors. That apparent motion can be used as a confounding cue has been demonstrated by Swisher and Hirsch (1972) who reported a much reduced temporal threshold when motion cues were used as additional cues than when otherwise.

In this context a study by Allport (1968) is an important example of the use of apparent motion not as an additional cue, but as the only cue. The assumption underlying that procedure was that failure to observe motion necessarily implies simultaneity. Allport's study has been used as the basis for rejection of a particular class of model of a central temporal processor (e.g., Broadbent, 1971; Turvey, 1977). For this reason it is particularly important to understand its limitations.

Allport's basic technique was to display several lines one-at-a-time, displaced vertically on a television screen. The ISI or on-off cycle of the lines was varied so that with an ISI of appropriate duration the lines might appear to be in motion, a phenomenon frequently used with electric signs to produce the appearance of motion. With a sufficiently short ISI, the motion is not present and all of the lines appear to be present at once. The threshold of motion vs. non-motion was the dependent variable.

The particular class of apparent movement or phi phenomenon used by Allport, known as beta movement, is that in which there is an apparent movement of a stimulus from one space to another. The stimulus conditions employed by Allport conformed to the experimental requirements of this type of movement,

although generally it has not been studied with more than two stimuli (but see Crook, 1937). A number of excellent reviews are available (e.g., Graham, 1965; Woodworth & Schlosberg, 1954) all of which are consistent in concluding with considerable confidence that the conditions for beta movement depend critically upon the time between stimuli, the duration of stimulus exposure, the distance between stimuli, and the relative intensities of the stimuli. In other words, the experience of apparent movement depends upon exactly the same characteristics as does the judgment of which stimulus appeared first.

Does that mean then, that both temporal order and apparent movement are equally good criteria for determining visual phenomenal simultaneity or successiveness? In fact, when apparent motion is possible, it is just the opposite; they are equally bad. Wertheimer (1912), as reported by all reviewers, performed the most extensive series of studies of the beta phenomenon and reported that, other things equal, with ISIs of 30 msec the two stimuli are reported as occurring simultaneously; with intervals of about 60 msec "optimal movement" (apparent movement which simulates real movement) appears, and at about 200 msec succession appears. Allport's critical temporal interval varied from about 70 msec to about 96 msec which conforms roughly to the apparent movement threshold of Wertheimer, but which is far removed from either simultaneity or successiveness.

Actually, Allport's subjects were easily able to judge the direction of motion of the lines. However, that judgment, as with the judgment of motion, was made in the presence of 12 successively displaced lines. Thus, the subjects had a large series of both spatially and temporally displaced events upon which to base a judgment. That they were able to judge both motion and successiveness, then, may have been the result of the opportunity to take many samples of the stimulus events, a procedure which would not seem

to test resolution as such, as well as to take advantage of the interaction between spatial and temporal factors in the situation.

Now the only difference between the spatially arranged, temporal-order-judgment experiment and the apparent-movement experiment is in the instructions given to the subject. In the one case temporal occurrence is judged; in the other, motion is judged. The literature of both kinds of experiment has stressed the importance of instructions and what cues the subject should use. In a very nice auditory study, Babkoff (1975) illustrated the difference between a confounded and unconfounded judgment by obtaining a psychophysical function not only for temporal resolution as such, but separately for a function representing the peripheral interaction of the judgment and the stimulus characteristics. On the other side of the coin, in reviewing the phi phenomenon, Graham (1965) placed particular stress on the importance of instructions to the subject about what to look for in the stimulus. This may be why investigators of temporal order using spatially separated stimuli do not generally mention apparent motion as experienced by their subjects, whereas investigators of apparent motion tend not to mention temporal order experiences. In any case, the conclusion remains that where there is an interaction between intramodal stimulus dimensions, unconfounded measurements of temporal resolution cannot be obtained without taking them into account. On this basis, Allport's data do not reflect temporal simultaneity or temporal order, nor do they provide a test of central temporal processing models regardless of claims to the contrary.

We now consider stimulation of the same retinal area twice in succession. Among the events which may result are: (1) the seeing of two stimuli in succession, (2) seeing the second stimulus only, which is called backward masking, (3) seeing the first stimulus only, which is called forward masking, (4) seeing both stimuli as simultaneous, or (5) seeing one stimulus which is a combination

of both. In the classical literature, it is well-established that there is a reciprocity between the luminance and duration of light so that the sole determiner of the brightness threshold for brief flashes or of a brightness match is the time integral of luminance up to a critical duration usually taken as 100 msec (dark-adapted eye; the light-adapted eye is 30 msec, according to Graham and Kemp, 1938). This function, Velden's Law (1944), has been demonstrated repeatedly in psychophysical studies to be operating on the optic nerve of Limulus, (Hartline, 1934), and very importantly for the present discussion to hold for both single flashes or for discrete pulses (Davy, 1952).

The masking literature differs operationally in that the masking stimulus is very often a complex random a-rangement of dots and/or lines while the test stimulus is one which can be identified by the subject name, e.g., a letter. As long as the stimulation is monocular or binocular, however, it must be assumed Bloch's Law operates. The question is whether some other law also operates, and whether Bloch's Law or something like it operates centrally as well. If the data can be accounted for solely by Bloch's Law, no second law need be invoked. This is a statement of the integration hypothesis of masking (e.g., Crawford, 1947; Ericksen, 1966; Kinsbourne & Warrington, 1962a, 1962b; Schiller, 1968, 1969; Turvey, 1973). We shall not distinguish between expressions of the integration hypothesis which assume that the effect is due to retinal processing and those overtake versions of it which assume that it occurs later in the peripheral transmission. The point is that it is a peripheral hypothesis which assumes that the critical conditions are total energy limited to occurrence within a critical time.

If the integration hypothesis is to account for monocular masking effects, it would be expected that the target-plus-mask combination would produce a third combined stimulus rather than the mask in its original form. Random

visual noise is commonly used for the masking stimulus and when that is done, the expectation cannot be tested since in the time available it cannot usually be determined whether the subject perceived the original random arrangement or one biased by the test stimulus. However, Uttal (1971) has shown that if the mask is varied so that such a bias can operate and be detected, the subject can actually report the test stimulus in the presence of the mask stimulus even when both are presented simultaneously. Another form of support has been provided by Ericksen and Collins (1968) who have shown that two irregular dot patterns in succession will meld into a third meaningful pattern as long as the ISI does not exceed 100 msec. In many of these studies, stimulus intensity was varied with results indicating that the stimulus energy is critical to the masking effect. It seems, then, that the integration hypothesis can account for the phenomena found with monocular presentation of two stimuli to the same location with separation intervals up to 100 msec.

Dichoptic presentations of the two stimuli so done that the stimuli fall on retinal areas within which fusion of the two stimuli is possible yield different results. Masking occurs only for masking patterns which carry information as opposed to meaningless pattern (e.g., Turvey, 1973); intensity of the masking stimulus is not an effective variable (Boynton, 1961; Schiller, 1969; Turvey, 1973). Also, while monocularly both forward and backward masking are effective masking procedures, dichoptically forward masking is relatively ineffective compared to backward masking (Turvey, 1973; Yund & Effron, 1974). Furthermore, the effectiveness of the mask depends importantly on an interaction between the duration of the mask and the onset-onset time (SOA) between the two stimuli (Haber, 1969; Kahneman, 1968; Turvey, 1973).

If this information, along with other dichoptic masking studies, is compared with monocular masking, two critical time constants are suggested. The

monocular data suggest that integration of two stimuli will not occur if the temporal separation (offset-onset) exceeds 100 msec. The dichoptic data seem to suggest that the stimuli will be seen as independent, non-interacting stimuli if the ISI exceeds 30-50 msec, or the SOA exceeds 30-50 msec. What the critical time will be monocularly depends upon stimulus energy whereas what it will be dichoptically depends upon stimulus duration and the informational aspects of the stimulus.

It appears, then, that failure to resolve two events temporally may result from integration in the peripheral system or as a result of a central process. One explanation of the latter that has been suggested is the interruption hypothesis (Kahneman, 1967; Sperling, 1965) according to which integration does not happen at all. Instead it is proposed that the second, masking, stimulus interferes with processing of the first at a central level, or "erases" it. This hypothesis is weak, however, since it does not account for either dichoptic fusion of dissimilar stimuli which we shall demonstrate later, nor for monocular forward masking. Turvey (1973) has proposed a "concurrent-contingent" theory in which the two processes overlap in time, but one still depends on the other.

Central Processing Theories. All theoretical approaches to a central processing mechanism rely upon three common assumptions: (1) the arrival times of the signals transmitted from the receptor(s) to the point of resolution or decision are independent, (2) all signals leaving the receptor persist long enough to reach the central mechanism, (3) the resolution occurs early in the total sequence of information processing. Sternberg and Knoll (1973) provide an outstanding analysis and integration of available theoretical approaches. A difficulty with all of them as formulated by Sternberg and Knoll is the requirement that the arrival times be resolved by an active decision process of some kind (or homunculus). Sternberg and Knoll are less concerned with the

nature of such a decision-maker than with the information on which it operates to make its decision, and the manner by which the decision may be expressed formally. However, the concept of an active decision-maker must be faced at some time in terms of where it operates in the information handling sequence, its capacity, and its interrelationships with other components of the system. We prefer to face that now. Furthermore, if it is possible, we prefer to work with a concept in which time resolution is not an active decision, but a reflexive or passive one and, thereby, to minimize the number of homunculi in the overall processing system.

Kristofferson and his associates (1967, 1970) have provided the most intensive effort to develop a central temporal theory although fundamentally he has been concerned primarily with the idea of an attentional switch which directs signals to a single-channel processing system. His theory rests upon *the following fundamental assumptions:* (1) signals from independent sensory channels are gated one-at-a-time to an attentional switch, (2) each stimulus signals the attentional mechanism, but the mechanism can only switch channels once every 50 msec, and (3) to resolve temporal order attention must be switched to each stimulus channel and the signal that is accepted as second to arrive must arrive <u>after</u> attention has been switched to its channel. The theory leaves available the possibility of voluntary control of attentional switching so that even if a signal is given to switch, the attentional mechanism may not do it. Kristofferson has been very successful in accounting for a considerable variety of latency data with this model.

Another well-elaborated concept of a central timing mechanism is the perceptual or psychological moment proposed by Stroud (1955). The fundamental postulate is that there is some kind of scanning process which has a constant periodicity. When two events fall into the same scan interval, they are taken

as simultaneous. If they fall into different intervals or moments, they are taken as successive. With this simple concept, Stroud was able to account for a wide variety of perceptual phenomena, and by extending it, he was able to bring the theory to bear on such issues as rhythmic responding, speech intelligibility, etc. The extensions of the basic idea, however, should not be used to evaluate the fundamental concept since they require additional assumptions.

Stroud's funcamental concept rests upon the observations made that brightness summation is the time integral of stimulus energy. Considering that and various other kinds of information, he concluded that the quantum of psychological time, the psychological moment, is 100 msec in real time with a range, depending on particular conditions, of 50 to 200 msec. From the above discussion we would conclude that Stroud was describing peripheral processing, but assigning it to central function, or treating both as central.

Nevertheless, the basic concept of a central scanner which provides discrete moments within which the temporal aspects of stimulation are quantized (so that psychological time is discrete rather than continuous), is attractive because it allows for the handling of non-peripherally determined simultaneity and, as will be shown, it lends itself to an understanding of how time, itself, is processed. Of the two proposals, Kristofferson's and Stroud's, we find the latter more amenable to a wide variety of phenomena and more parsimonious. We shall adopt Stroud's basic idea, therefore, and assign it to the a-function when that function is detailed further below.

An alternative to Stroud's fixed moment is the notion of a running sample taken between pairs of successive events, i.e., a traveling moment as proposed by Allport (1968). The question of whether central temporal processing is discrete or continuous has implications to the fundamental postulates of any theory of information processing. A discrete moment hypothesis leads to models which

assume that the human system "sees" and processes a succession of snapshots of its environment. A concept such as the traveling moment leads to models which assume a continuous outlook. However, although the fundamental postulates are essentially different, they come closer and closer together as the magnitude of the discrete moment decreases. Under all conditions, a model based upon a quantum unit of psychological time is an estimate of a continuous time model. Thus, even if the continuous model more nearly approached reality, the discrete model would provide a useful, and certainly mathematically simpler approximation.

To our knowledge, the study by Allport (1968) discussed above is the only serious challenge that has been offered to Stroud's concept. Interestingly, it has been accepted widely as incontrovertible evidence against the concept and for that of a continuous processor. Turvey (1977) has used it as the basis for the rejection of all snapshot-like theories which is in effect the rejection of all current approaches to human information processing. This is unfortunate since, as we indicated above: (1) Allport's measure did not reflect temporal resolution nor, therefore, did it test the hypothesis of a discrete, central moment, and (2) Stroud's own formulation was based largely on peripheral events. Furthermore, the fixed moment concept allowed to be part of a continuous duty scanning system is closer to the reality of a continuous duty organism than a concept which must wait for a unique stimulus to trigger it, or which must measure a difference between each and every stimulus event it receives.

The Whole a-Function Model

In discussing the response criterion model illustrated by Figure 3, nothing was said about the characteristics of the RC other than that it represents an accumulated number of neural pulses or of sensory evidence necessary for a response or further processing. Available counting models have not included an attempt to specify what the pulses are evidence of other than that they are

those effects of stimulation which are used for a sensory decision. On the other hand, some theories of information processing have included detailed proposals for the nature of sensory evidence. With one or another variation, these proposals have been for patterns of stimulation on the basis of which template-matching decision is carried out later in memory, or a feature-matching or feature-combining model is proposed in which features are analyzed or compared at one or more times. Excellent reviews are available (LaBerge, 1976; Sutherland, 1973). Without belaboring the issue, the idea of a template as so far conceived does not seem to have substance, and we shall say no more about it.

The theoretical treatment of stimulus features is, itself, complex and breaks down into those features which are processed peripherally and end up as coded neuronal events in the cortex, or those features of the stimulus which are necessary for identification, and whether or not there is a feature-processing mechanism early in the system which is reflexive, or which is tuned selectively by the needs of higher (or later) processes. With regard to the last, it should be apparent that the present proposal does assume control of the a-function, e.g., the RC level, by the requirements of later processes (M:S) and, in this sense, agrees with Hebb (1949). See Carr and Bacharach (1976) for an outstanding discussion of this issue.

We are now concerned with the nature of stimulus features and of the RC. We start by observing that all feature-detection or analysis theories available are in the awkward position of having to account for the enormous variety and richness of perceptual phenomena, by relating that variety to an indefinitely large collection of features, feature variations, and rules for combining features. Features have been suggested to be receptor analogues, e.g., movement, contours, angles, lines, etc., or they have been identified from the response

side in terms of stimulus characteristics which are confusable. Features have been defined as values on a dimension, or as combinations or simpler stimulus properties such as phonemes and graphemes. We take only one issue with these approaches, and that is that they all ignore the manner in which human perception seems to operate. In fact, as observed by Miller (1956), LaBerge (1976), and Sutherland (1973) to mention only a few, people can do very little with absolute values on a dimension. There are a limited number of colors, brightness, tones, etc. which can be recognized as such. On the other hand, the human organism can resolve very small differences between values on a dimension. We propose then that it is not absolute values which are "features," but relative values, and more specifically based on the work of Stevens (Stevens, 1975a, 1975b; Stevens & Galanter, 1957) and his colleagues, that a feature is a ratio of actual stimulation to an identifiable absolute value on a dimension. Consequently, an RC is a desired ratio of the same sort. Note the similarity of this statement to the Weber-Fechner (Fechner, 1966) formulation.

Consider a situation in which it has been learned that a particular form has what in ordinary terms we would call a certain brightness, size, orientation, etc. In the present terms we mean that along each dimension it bears certain ratios of stimulus effects to references along those dimensions. Suppose after familiarity with the form in a constant stimulus context, the stimulus parameters were altered so that the form were now brighter, larger, and oriented somewhat differently. For the form to be identified correctly, the ratio criteria must not change. That can be achieved by changing the absolute reference, keeping the ratio the same. Note that the more reference values than can be employed along a dimension, the greater the precision with which ratios can be used.

In these terms an RC model would assume that evidence is accumulated not as the absolute number of pulses accumulated, but as a changing ratio of actual stimulation to a reference level. To do that requires a system which can provide a reference value for each dimension and a value for the accumulating evidence, and which can maintain a running calculation of the ratio of one to the other. Is there any basis for supposing the existence of such a possibility other than psychophysics? We do not know of any in terms of empirical findings, but we shall, very hesitantly, speculate.

First, it is well-accepted that the visual cortex consists of layers of coded detectors representing lines, angles, and other geometric properties of the retinal image. It has also been demonstrated that some cortical neurons are not simple in that sense, but are complex and hypercomplex representing specific arrangements of light distribution on the retina (Hubel & Wiesel, 1965, 1967, 1968). These findings are frequently cited. What is less often noted is that all of these coded detectors appear at least twice.

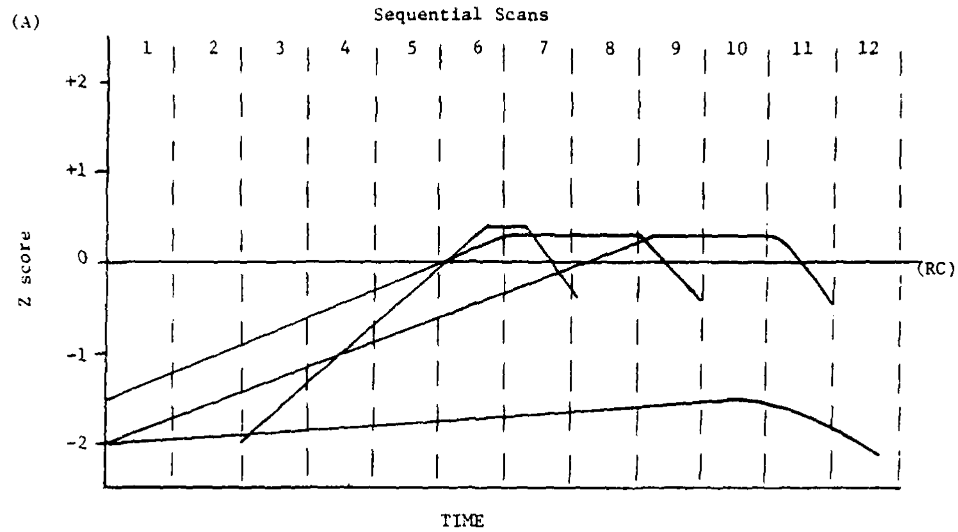
To our knowledge the significance of this multiple representation has not yet been determined. We speculate, therefore, that one representation is of a reference level as described above; a second one is of the receptor output. As noted above, a computational mechanism operating upon the ratio of these two along a single dimension could indicate when a criterion ratio was met. We shall not speculate as to whether there is a separate neuronal representation for each reference, or whether there is a single neuronal representation which is variable so as to allow it to take on different reference values. We note too, that what is suggested is not the only way that one might conceive of a system which defines its features in relative terms.

Among the advantages of such a system is the possibility that all features might lie on the same physiologically-determined dimension, and thus, speak a

common language, as it were. If so, it might then be possible ultimately to transform from each of the various dimensions now used to describe sensory events to that common dimension. A model of such a system would need only to be able to code by feature (perhaps by location) and by a criterion ratio.

Having now proposed a response criterion model which employs relative, rather than absolute,evidence, we must admit that we are not yet ready to exploit it. The similarity of the relative RC concept to the comparator of a proportional control system is striking, but we have no basis for estimating the transfer function if the system is linear, let alone the differential equation for it if it is not. Therefore, for the present theoretical effort, we shall assume an absolute feature model as an approximation, but we do so with the understanding that it will probably have to be modified at some future time. On the other hand, it should turn out that it would make little difference. That is, the same concepts may be applicable to the idea of a cumulated amount of evidence as to that of a changing ratio although the mathematics of the models expressing them might have to change from a discrete to a continuously varying measure of evidence (unless ratios turn out to be sampled intermittently). The same could be said about a control theory model if only the transfer function were used.

Figure 4 illustrates the incorporation of a discrete moment scanning model into the a-function. The vertical dashed lines represent the operation of a sequential scanner which indicates or transmits to STS data representing all those stimulus features which have reached RC within each scan interval. It is assumed that the scanner contacts every RC in one moment, and transfers all of the RC "activated" data simultaneously at the end of the moment. If we assume for discussion that it takes 25 msec to complete one scan, then all features represented within a 25-msec scan interval are taken as simultaneous, and



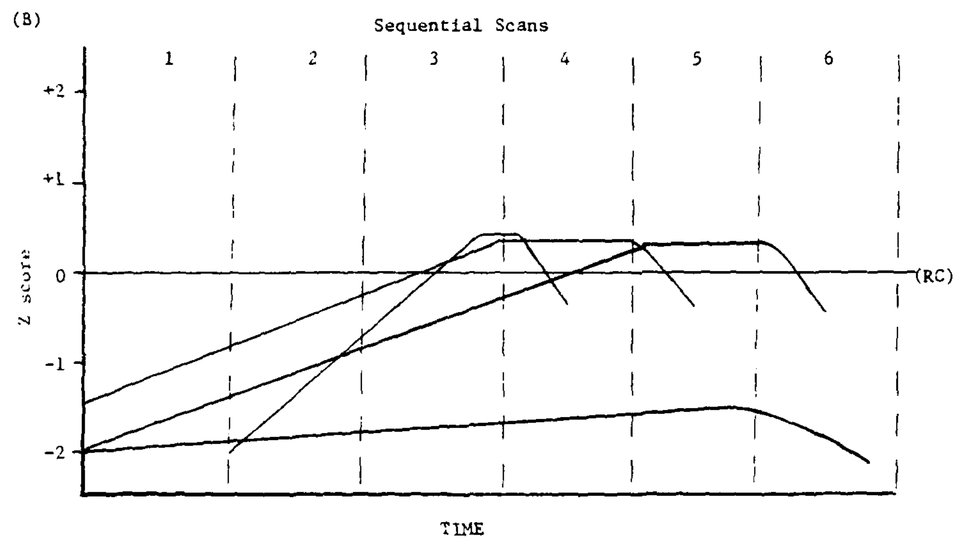


Figure 4. Response Criterion Model with Discrete Moment Scanning.

depending on location coding, as characteristic of one stimulus. This does not mean that all features arriving with 25 msec of each other will necessarily be taken as simultaneous for they could fall into different intervals. That is, the scanner is assumed to be on continuous duty so that the particular interval within which enough feature evidence had accumulated to reach RC is unpredictable without exact knowledge of the instantaneous scan pattern.

Figure 4 also illustrates the assumption made that the persistence of the stimulus is inversely related to its intensity. This is shown by the trend of the lines. In all cases, they rise to a limit, remain there for a period of time which is inversely related to their slopes, and then decrease. The scanner reports the presence of a stimulus only when it is at or above RC. Thus, stimulus D would never be reported.

Figure 4a differs from Figure 4b in the cycle rate of the scanner. If Figure 4a is supposed to have a 25-msec scan interval, Figure 4b will have a 50-msec interval and, thereby, represent the effects of a lower activation level, whether controlled indirectly by M:S or partly as the result of external events or body state. It may be seen in Figure 4a that even though Stimulus C was initiated some time after Stimulus B, and each with the same criterion, it would appear to have preceded it in time since it arrived at RC during an earlier moment. Furthermore, these two stimuli would not appear to be overlapping since they do not share a common moment at or above RC. On the other hand, Stimuli A and C will appear to be simultaneous even though Stimulus C started later and was taken to a greater criterial level. As shown, Stimulus A would appear to have the same onset as C, but a longer duration. On the other hand, with a slower cycle rate, as in Figure 4b, Stimuli A, B, and C will appear to be overlapping for a period of time.

Suppose, in Figure 4a, that A were a relevant stimulus and B were irrelevant. Then response would be to A. However, if B were more intense, it could arrive in an earlier moment than A and, thereby, elicit an erroneous response. Similarly, if C were irrelevant, it would interfere with A as shown. One solution would be to increase the intensity of Stimulus A. In fact, raising the intensity of a relevant stimulus is a common way to increase the probability of response to it. Similarly, a relatively intense irrelevant stimulus is an effective distractor.

An important question concerns cases where a relevant and an irrelevant stimulus have features in common. In such cases the RCs for relevant features can be set relatively low, and the decision based upon combinations of features so selected. It is unlikely, however, that the RC could be set low enough to avoid all irrelevant features.

Suppose a relatively large visual scene, one that extends outside of foveal vision. In that case, the transmission times of peripheral features will be longer than central ones and may fall into later moments, assuming the same RC levels. In fact, this is a common experience in recall of a scene. Peripheral events tend to become lost (do not reach critera) or delayed in processing (fall into later moments). Central events are reported first which we interpret as reflecting different transmission times (e.g., Rutschmann, 1973). This effect could be compensated for by a lowering of peripheral RCs. Note that such events along with the manipulation of RC levels accomplish what has often been accounted for with some kind of attentional mechanism. That is, the deliberate lowering of an RC or a group of RCs would be accomplished if all sensory inputs were equal and simultaneous and some kind of mechanism operated selectively with respect to them. The difficulties in specifying the characteristics of such a mechanism beyond stating that it exists, for example as some

type of filter (Broadbent, 1958), seems very great. Note, though, that the present model may be viewed as a filter with attenuating properties as suggested by Treisman (1969), but with allowance for loss of the stimulus. Its advantage lies in its simple quantitative formulation, and in the combination of the RC and the scanning models.

Reference back to Figure 2b shows that the a-function is influenced by the activation mechanisms. We have already discussed one postulated effect of activation, the lowering of RCs, and mentioned an effect on the scanning rate. We now postulate formally that for any task there is an optimal scan rate and, with experience that rate approaches the optimum under constant conditions. Direct influences of stimulation on the arousal level also affect the scan rate. In both cases, it is assumed that the scan rate increases as the activation level increases. One result of an increased scan rate is that features, which, under optimal conditions fall into the same moment (or into different moments) may now fall into different (or the same) moments resulting in a confusion among features, interference with identification, and an increased probability of wrong response. Similarly, a decreased arousal level, for example with drugs or sleep loss, would decrease the scanning rate leading to a confusion of temporal orders so that stimulus features normally combined into different stimuli will not only be improperly combined, but will appear to be different stimuli in odd temporal orders.

A related effect would happen with time judgments as such. If we consider each moment as a unit of psychological time and the number of moments in which a stimulus persists at or above its criterial level as psychological duration, then with increased activation, the duration of an event would seem to be longer than normally, whereas with decreased activation it would appear to be shorter.

These expectations appear well-documented in drug studies as well as other studies of temporal duration.

Interactive Relationships and Summary of the a-Function

The function of this primary step in central processing is to make available to STS those stimuli which are to be given further processing. The a-function is not a detector in the sense that a decision is made about the presence or absence of a signal. Rather it is a selector, the output of which is used to made a detection decision, or an identification, etc. Those are memory processes to be discussed in the next section. However, it is in those processes that decision criteria reside which determine the setting of the RC and the scan interval.

The fundamental assumptions of the present RC model are simply: (1) that the processing rate to the RC increases as stimulus energy increases, (2) that stimulus persistence is very limited, and (3) that RC varies normally from trial-to-trial. We have assumed, in addition, that persistence is inversely related to intensity. The fundamental assumptions of the scanner are that: (1) only those stimulus events which are at (or above) RC are reported as present, (2) that they continue to be reported in each moment during which they remain at RC level, (3) that all events at RC level in any moment are transmitted to STS as simultaneous events, and (4) that the apparent or psychological duration of an event is simply the product of the moment length and the number of moments during which an event is at RC. Because events within a single moment are simultaneous, one event may mask another, or the two events may fuse or meld to provide the perception of a third event. Similarly, temporal simultaneity, successiveness, and overlap are explained by the moment hypothesis.

We shall assume below that the persistence of a stimulus event in STS is also limited although to a different order of magnitude. Since stimulus processing occurs only while the stimulus is in STS, it is to the advantage of the system to maximize persistence in STS. The only way that can happen is if the stimulus persists at RC level so that STS can be refreshed by stimulus occurrence over successive moments. But since the stimulus can persist at RC for only a brief time, the system gains persistence in STS by setting the RC level low. That is, the lower the criterion, the sooner it is reached, the greater the proportion of its persistence at RC level, and the more moments into which it will fall. Therefore, the longer it will be represented in STS. Accordingly, it would be expected for short-duration stimuli, that the larger the M:S set size, or the greater the stimulus uncertainty, the lower the RC level. It is available through a number of comparisons in memory.

A penalty is paid for that persistence, however, since as the RC level decreases, the probability of error increases. This actually permits some very interesting predictions. First, it can be predicted that the lower the criterion, the greater the probability of false alarms, i.e., processing the "activated" RC as a stimulus event when noise, but no stimulus occurred. On the other hand, it can be predicted for very brief stimuli and relatively large stimulus uncertainty, that the lower the criterion the greater the probability of a hit given that higher RC levels reduce the time available for processing in STS. Thus, unlike the theory of signal detection, the probability of a hit need not be inversely related to the probability of a false alarm.

The second prediction does not hold for stimuli which have long physical durations. In that case, it is to the advantage of the system to set the RC relatively high (unless there is a cost for time) and maximize correct RC energization. That would decrease the probability of false alarms without a

time penalty in STS. Under such conditions a speed-accuracy trade-off would be expected, and the probability of a hit would be inversely related to the probability of a false alarm.

Stimulus Memory and the S-S Translation

The stimulus memory stage functions as a means to effect various kinds of stimulus transformations until the stimulus is in that form in which responses have been associated with it. We shall make no attempt to face the problem of how response associations are formed, but we shall be concerned somewhat with the effects of different levels of learning on the translocation processes. Similarly, we shall not attempt the enormous task of sifting through and evaluating the large number of memory models and theories which are available and which are still accumulating at an alarming rate (and which we are not alleviating). For the most part those models appear to be examples of the possible rather than the probable. Regardless, we readily admit their influence, and influence which must already be apparent from the earlier discussion of the theory in general. Thus, we take the position of a widely-held view that information is first established in a sensory register, and that it is that information upon which the first coding operations are performed. We differ from some such views, however, in that we have not allowed those coding operations to be performed on the information while it is in the sensory register although a pre-set coding operation is performed by how the RC and the timing mechanism are regulated. The information which is output from the a-function is held for a further period of time in a STS, and it is only after storage there that stimulus transformations begin. Those transformations are accomplished as a series of coding operations carried out in a working portion of LTM:S which we have called M:S.

Our fundamental approach to this stage of processing is that what happens in M:S is a series of time-limited transformations. Current theoretical approaches to memory are concerned with what kinds of structures can accomodate those transformations. Little attention has been given to the transformations as such in a systematic way except to attempt to identify the kinds of coding dimensions (e.g., phonemic, semantic, verbal, sensory attributes, images, etc., etc.) which might be used and the organization of storage which might prevail. While those are certainly important activities, an at least equally important step is the development of a systematic way to quantify transformations as such so that memory research may be based upon quantitatively variable independent and dependent variables, and so that functional relationships may be established. For this purpose, it is easier both theoretically and analytically to assume that each stimulus transformation is to a single scale and that transformations provide a viable postulate given the rest of the present theory.

As indicated earlier, each stage of processing may be viewed as a subtask in the overall task process, and tasks are transfers of information. In the stimulus memory stage, tasks are transfers of information from one stimulus code to another. Without regard to what the codes may be in a literal sense, the nature of possible transformations has been described by Posner (1964) as translations of identification (conservation), classification (condensation), and creation. We shall add to those translations <u>compression</u> and a variant of creation which we shall call <u>decoding</u>. The distinction among these translations lies in the nature and quantity of the information transfer.

Identification refers to a one-to-one mapping or translation from one code to another in terms of message units. The amount of information per message is equal in the two codes. Thus, if a stimulus defined on a feature code were translated to a name, and if every stimulus in the stimulus set had a unique

name, the amount of information in the stimulus set and the name set is equal per message unit. Similarly, a word-to-word translation between two languages having isomorphic vocabularies would be a translation between names with no loss in message information. Posner called this conservation, therefore, but clearly conservation is equivalent to the identification of a message on one code in another code.

Suppose that the message units of the first code contained all four-letter words, and those of the second code contained all two-letter words. The translation is still one-to-one per message unit. However, there is now a reduction of information within units. This is an example of compression. A common example of compression within a single language is an abbreviation. The amount of compression which is possible is dependent upon the redundancy among symbols within messages, a very important consideration.

Creation is a few-to-many translation. We shall discuss it only in the sense of decoding, and that can happen in two ways. One is a translation from message classification to the contents of the classification. The other is from a compressed message to a full message.

Measurement Concepts

To our knowledge only Posner (1964) has proposed quantifying transformations, and then mainly in terms of the information reduction of many-to-few mappings. While information reduction, as he has proposed it appears to be a meaningful concept, and not unrelated to ours, there is a gain in treating all kinds of transformations within the same framework. In what follows, we present only the briefest version of coding theory as a descriptive source, and do so along with simple extensions from it which we believe are especially useful. Following that we shall consider some theoretical questions which the general concept of stimulus transformations brings to mind.

Assume a four-message binary source (S) which contains the following messages: 0001, 0010, 0100, and 1000, with probabilities of 1/4, 1/8, 1/2, and 1/8 respectively. The four messages could be recoded, for example, as: 00, 01, 10, and 11, with, of course, the same probabilities. From simple coding theory (Shannon, 1962) the average length of the source code (Ls) is:

$$Ls = \sum_{s_i}^{i=1} p_{(s_i)}(si) \qquad (3)$$

For the example, the average length of the source code is four bits/message. The average length of the recorded messages (Lc) is two bits/message. Thus, on the average, the Lc code is shorter than the Ls code.

The quantity

$$\mu_c = Lc/Ls \quad \text{with} \quad Lc \leq Ls \qquad (4)$$

is the average compression for a sequence of messages of a given length. This measure is an index of coding efficiency: the closer it is to zero, the greater the coding efficiency. The lower bound or limiting value of this quantity as the sequences get longer is the coefficient of compression. Equations 3 and 4 are illustrative of the power of coding theory as a descriptor of the S-S translation. Other aspects of coding theory offer possibilities for coding both noiseless and noisy situations, for very complex codes, and for the development of optimal recoding and decoding techniques as a reference against which human coding may be evaluated.

A criterion of goodness of any coding system is its cost. In the example, the recoding is less costly that the original coding because it allows more messages to be sent in a fixed period of time. That is, in terms of information transmission, time is cost. Similarly, if errors are involved, a decrease in error is a decrease in cost. For any task, then, a decrease in cost is related to a decrease in response time and/or error associated with an S-S translation.

Since both speed and error are represented jointly in the information metric, that measure may provide the basis for an index which reflects the effectiveness with which the translation or coding is performed by the individual. To develop such a measure, we assume, reasonably, that the rate of information transmission (R) increases as the compression increases, i.e., that R is inversely related to μ. Accordingly, we propose that

$$R = b(1 - \mu_C) \tag{5}$$

Therefore

$$CE_C = b = \frac{R}{1 - \mu_C} \tag{6}$$

whereby CE_C we mean the cost effectiveness of compression. So, the slope of the function relating to R to compression is a measure of effectiveness defined in terms of the change in R due to a change in compression, or it expresses R *per unit of compression*.

What is the source of variations in compression effectiveness? Ignoring the time required to make the S-S translation, the increased effectiveness of human information processing associated with S-S compression is the result of a subsequent decrease in translation time and/or error of the next translation. This is because the stimulus (message) which is now presented for translation contains less information than did the untranslated source stimulus. Note that the next translation might be another S-S translation or it could be an S-R translation.

What is added by the S-S translation time, itself? The same principle applies. That is, the less information in the recoded message (the greater the compression), the faster should be the translation, the less error in it, and the more rapidly it should be learned. As an intuitive example, it should be easier to translate from a four-symbol to a one-symbol message than if the

recoding were to a three-symbol message. Consequently, if an S-S translation is required, the greater the compression, the greater should be the speed and accuracy of the S-S translation. On the other hand, even maximal compression must involve more time than no recoding at all. Thus, one value of the cost effectiveness measure is its expression of the trade-off between successive translations, e.g., between the S-S loss in speed and the S-R gain in speed and accuracy.

S-S compression is only one of two possible ways by which a stimulus can be manipulated. As stated before, it may also be translated by mapping a first stimulus set onto a second one. For example, in the four-message set: 0001, 0010, 0100, and 1000, if all messages were sorted into those beginning with 00 and those ending with 00 and recoded as 0001 and 1000 respectively, we would have a case of four-to-two mapping without any compression. This kind of coding is classification and it is accomplished by a reduction of messages as opposed to a reduction of symbols. Similar to our derivation above, it is reasonable to propose

$$\mu_r = \frac{Hc}{Hs} \tag{7}$$

where μ is the average reduction of information per message, Hs is the average amount of information in the original or source code, and Hc is the average amount of information in the second code, i.e., the one to which the translation is made. As before, the rate of information transmission should increase as the reduction increases, or

$$R = K(1 - \mu_r) \quad \text{with} \quad 0 < \mu_r < 1 \tag{8}$$

and

$$CE_r = K = \frac{R}{(1 - \mu_r)} \tag{9}$$

where CE_r is the cost effectiveness of a reduction of information per message and is the slope of the function relating R to μ_r.

It is probably apparent that the same concepts will apply to increases, i.e., instances of decoding, as well. One important qualification must be made regarding learning. It is reasonable that the greater the level of learning at the coding or translation task, and the greater the familiarity of the individual with the codes, the greater will be R. Consequently, both b and K in equations 5 and 8 (or CE_c and CE_r) are functions of practice and familiarity. These learning functions need to be determined empirically to make predictions of actual performance levels. On the other hand, keeping them constant experimentally should be sufficient to test the concepts.

We have postulated an M:S in which translations are carried out serially. Accordingly, the processing rate over a series of translations will be equal to that of the slowest translation rate. Thus, if the translation rates can be determined separately, assuming no interaction, the rate of translation in series will be that of the slowest rate by itself. Here again, practice should be important. That is subjects should be given reasonably extensive practice under both single and combined translations to overcome practice effects that are peculiar to each.

S-R Translation

It is probably evident that the same concepts can be applied to the S-R translation as well. In this case, the recoded message is a response and it is defined by a response code. The effect to be expected of an increased reduction or an increased compression would be an increased speed and accuracy of response selection.

As soon as an S-S translation is involved, it becomes important to consider both the S-S and the S-R processes. One way to do that is to hold the recoded message constant in the S-S stage, use it in the original source. This is not unlike the situation in the learning of a new language in which the new

vocabulary is translated to the old one and the response is made to the translation. That is not the only way, of course, by which the translations may be studied. Everything but the response code can be held constant, or everything but the recoded set can be held constant.

Coding and our proposed measures of cost effectiveness were developed above in terms of binary numbers as messages. While such numbers can be used experimentally, it is also important to deal with visual symbols coded by dimensions such as color and shape, or with words and word units either in the visual or auditory mode, etc. Of great interest is that this approach allows for the direct calculation of symbol and of message redundancies and, therefore, a chance to apply Garner's (1974) concepts of redundancy in a systematic fashion.

All experiments require S-S and S-R translations of the subject although the number of translations and their complexity may be small as in detection or simple reaction time experiments. As the complexity and number of translations required of the subject increases we wish measures which reflect covert translation activities. Typical psychological experiments provide measures of response time and/or errors. Such measures are weak because they reflect the <u>effect</u> or <u>output</u> of all processes due to all causes. On the other hand, experiments which provide functional relationships permit the use of rates as measures of the activity of underlying processes with intercept values which reflect the effects of other, including uncontrolled variables. A case in point, regardless of theoretical interpretation, is the excellent demonstrations of Sternberg (1966, 1975) of the value of these two quantities as measures. Where possible then, the preferred experimental model is one which does provide relationships from which rates can be obtained.

The measures just proposed do provide rates as measures. Moreover, as discussed earlier, the RC model described provides a measure which can be

interpreted as an index of the rate of information processing. We shall show below that that measure does, indeed, reflect the operation of covert S-S translations. Alternatively, or in addition, R as just described may be computed from the same set of data.

The field is badly in need of more analytical methods based upon simple models which can be accepted widely and which reflect more than the total combined effect of all underlying processes. Elsewhere we have made an attempt in that direction (Teichner, 1979 in press) which provides a measure of input time, i.e., time from stimulus presentation to input into short-term memory to response initiation. Whether it is a simple holding device or a limited duration working memory is not a necessary assumption. Depending upon the conditions that prevail, input rate may also be calculated.

STS and the a-Function

STS as we have developed it theoretically is a representation of the last stage of processing in the a-function. It is therefore, a store of the stimulus or stimuli coded by features or attributes. It has a duration of a few seconds, and it is only during that duration that memory operations can be performed. This approach differs from other current conceptions in that STS provides no opportunity for rehearsal or transfer to LTM, not as it is viewed as a limited duration active portion of the LTM. It provides only a holding device. We differ also from the more recent versions of Shiffrin and his colleagues (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977; Shiffrin, 1977) in that we retain a distinction between the sensory processing or a-function and STS, a distinction made earlier by Atkinson and Shiffrin (1971).

As Shiffrin (1977) has noted, it makes little difference to their memory if the STS and the sensory register are handled separately or combined. This point may be made about most current theories since most of them fail to

provide operational distinctions between the functions of the sensory register and those of whatever follows. Thus, these theories assume the sensory register as a given, generally of unknown form, even the output of which is a matter of little interest (e.g., Bower, 1977a, 1977b). Contrary to this precedent, it should be an axiom of model or theory development, that two stages in series without independent operational definition are beyond meaningful distinction since they cannot be tested independently even within the requirements of the theory. This need for operational definition is not changed by "converging operations." It is true, then, that it makes no difference whether STS and the sensory register are combined in these theories or not since they are never provided with measurement concepts that distinguish between them. Even uncombined in the sense of verbal acceptance of their presences, they are combined operationally. The present theory keeps the two stages separate and provides a measure of the a-function, the RC, which describes only events in that function.

One of the differences between the theories of Shiffrin and his colleagues and some others is in terms of whether the early processing is a passive reception of stimuli or whether the system acts to manipulate that reception. As with the Shiffrin approach and that of Hebb (1949) and Gibson (1966, 1969), the present theory views the processing of stimuli as an active process. That is the RC and the scanning interval are established by expectations of what will occur. What gets to STS then are reports of which among the various expected events occurred (including very low expectations).

STS and M:S

We think of M:S as a stimulus set selected from LTM which functions as a working memory (cf. Atkinson & Shiffrin, 1971; Baddeley & Hitch, 1974; Patterson, 1971), but with successive transformation stages carried out within

it. Also, M:S, as we view it, is not a short-term memory. It does not decay with time. The first stage of M:S is always a search among sets of relevant and of irrelevant stimuli coded along feature dimensions. Since all of the items which fall into a psychological moment are transferred simultaneously to STS, those items are represented in STS as simultaneous. Nevertheless, they are considered one-at-a-time in the search through M:S. This search we designate as STS-S_1 and mean by that that a particular item is compared against the feature-coded items of M:S in much the same sense as Sternberg (1966, 1975) conceives of memory scanning and recognition.

We have assumed that with appropriate signals, instructions, priming, post-stimulus cuing, etc. the system can select and organize an M:S of transformation sets correlated with the first stage positive set based on previous experience, which is appropriate for the task. Thus, when an item in STS has been identified, it is in terms of which of the pre-established set it is. This differs from the case where the item cannot be identified in the positive set, nor in whatever negative set that is established at the same time. Such an item may be an alarm signal, or it may be one with enough features in common with members of the positive set to have reached criterion, but for a which a match in M:S was not then found. In that case, as shown in Figure 2, STS is re-inspected, the match is attempted again, and if it fails again, a signal to LTM:S leads to the selection of a new positive and negative set. It is reasonable to assume that the M:S search and looping back to STS will be repeated successively each time comparing the item against fewer items in the positive set until some level of confidence of a mismatch is reached. The new selection from LTM:S is presumably based largely on those features of the stimulus which make it different from the stimuli of the original set.

The search in LTM is one among features which define or code classes of stimuli. The positive set established in M:S is a selection of one or more groupings within some classification code, but decoded so that an individual item in STS may be compared within the grouping. Thus, we can conceive of two kinds of search processes as the first processing activities of LTM:S. The first is the identification of a class of items, and that may result prior to the initiation of the first trial of an experiment as a result of an instructional signal. It may also be the result of the appearance in STS of a stimulus which does not match what is in M:S. The second is an identification of which item within the class best represents the stimulus in STS. Both are one-to-one translations or identifications even though one identifies on a classificatory code. Both involve searching. One is a <u>what</u> hunt; the other is a <u>which</u> hunt.

The items in the M:S are first feature-coded, but only with respect to those features which have previously led to successful performance. With learning, irrelevant or non-contributing features drop out (compression). However, in establishing an RC level, it is generally not possible to "filter out" all of those features, so that what is in STS contains more than critical features. Memory search, then, is generally a comparison of stimulus message items in STS which contain more features than those in M:S. That is, memory search involves a translation to a compressed code as part of the search operation. Early in learning the greater the number of additional features and the greater the frequency of partial correlations among features, the longer the search time. When learning is very advanced, only the correlations (redundancies) remain as important. At any time it is to the advantage of the system to set the RC as low as possible consistent with obtaining critical features.

We might observe at this point that whatever the ultimate transformation in a particular task, there would be an advantage to the system in establishing

the RC to detect features which define that code, and thus bypass all transformations to it. The difficulty that arises in making this inviting assumption is that it makes the RC and the memory system completely redundant, and thereby obviates an experimental distinction between them. We shall propose operations which lead to the minimizing of transformations with learning, but will assume that they happen within LTM:S.

We are supposing that, given the existence of a positive set in M:S, there is always a one-to-one transformation on a feature code, and that with learning the amount of compression of the code in M:S increases. That transformation may in turn be followed by another identification, or by a classification, or in certain cases, by decoding. That is, on the assumption of a series of transformations in the organization of memory, partially assigned to M:S, the positive set in M:S could itself be a feature-coded representation of a higher order transformation in cases where feature representation is possible. Consider the possible situation in which the stimulus set consists of a large and a small circle and a large and a small square. They are presented one-at-a-time and the subject's task is to press one of two buttons according to whether the presented stimulus is round or square. We shall then suppose that the subject transforms that item on a one-to-one basis to a name which might be "large circle." The transformation sequence is now STS-S_1-S_2 and consists of two successive identifications. Now suppose that the stimulus is assigned to the class "round." That, then, is the final transformation on which the response will depend and the sequence is STS-S_1-S_2-S_3-R. With continued practice, however, this situation allows for the size feature to drop out of the positive M:S set and for the shape feature, thereby, to provide a clear definition of the two classes. Accordingly, the response may become associated directly with the feature definition and the sequence can be described as STS-S_1-R.

Other examples could be considered in which the classification was with respect to some peculiarity of the name code so that even though the transformation from the feature to the name code remained the same, the relationship to the classification was different. That might be the case where the name code was articulated in such a way that it could be grouped in a manner not consistent with the feature grouping. In this case, the grouping step could drop out and the response become associated with the name code directly. Furthermore, it is likely that the name code will have become compressed as far as possible consistent with translation from the feature code.

Although everything has limits, we place no bound on the nature nor number of translation steps that could be involved in processing a stimulus. In actuality the number of successive translations is probably few, perhaps no more than three to five as a maximum. The completion of S-S translating is indicated by the initiation of an S-R translation theoretically. This and the postulation of a series of S-S translations pose a problem in operational definition. Having postulated a series of translations, how can they be distinguished at least with regard to thier number and temporal order let alone the nature of the codes involved? The answer to this problem is one of successive experimental comparisons starting with the simplest experimental arrangement, e.g., one required operation, and increasing the transformation demand systematically. As noted earlier, on the serial assumption the overall rate will be that of the slowest rate. The total time, however, should increase systematically with the number of translations.

We propose that certain kinds of responses act as what might be called augmenters. That is, the stimulus consequences of making the response (response-produced stimuli) provide new symbolic stimuli to the system which, after appropriate processing lead to additional S-S translations, but now with an

altered stimulus set. Subvocalization is probably the most common example of this. As possible examples, rather obvious subvocalization is often found in reading and at certain stages in the learning of a foreign language. In both cases it can be supposed that stimulus processing is carried to some translation where it elicits overt responses. With sufficient fluency in the language or with sufficient skill in reading, this step might drop out leaving the overt response tied directly to a translation in the original S-S sequence.

By their very nature augmenting responses provide a means by which stimuli appropriate to the task remain in STS in the absence of the original stimulus representation. For example, the brief sight or hearing of a telephone number will have limited duration in STS. If the number is vocalized, however, the response-produced stimuli represented in STS will be appropriate for translations leading to a response even though the original stimulus representation will be gone. Of course, not all augmenting response need be vocalization or subvocalization.

Note that an augmenting response is actually an example of completed processing since it represents t e total S-R transmission. Although we are not concerned with mechanisms of learning here, it is worth pointing out that we can view a completed S-R event as a rehearsal, and as such as the fundamental unit on which learning depends. Thus, one effect of an augmenting response is an increment in the establishement of events in LTM:S and LTM:S-R.

Mediating stimuli. It is now generally asserted that: (1) paired associate learning proceeds via mediating stimuli which are hypothetical coding events intervening between the associates (e.g., Martin, 1972; Richardson, 1972; Simon & Newell, 1972; Underwood, 1972), and (2) that usually memory skills are achieved by the use of a standard (for the individual) set of stimuli, usually chunks, which intervene to connect presented items with the recall of those

items. These appear to be the same concepts. Of immediate interest is that they can be expressed here as a transformation stage selected on the basis of an appropriate classificatory code. The same code may be useful in a wide variety of situations.

Memory phenomena as criteria. It has been stated that no theory of memory is adequate unless it can account for the effects of recency, primacy, and the bowed serial curve, among other phenomena (Norman, 1970; Saunders, Smith & Teichner, 1974). As studied, those effects are not identified with respect to what kinds of transformations they go through. We suggest that there could be a gain in identifying those transformations to determine whether or not these phenomena are likely to occur in different transformation stages. Similarly, it might be profitable to determine the locus of order effects whether in a particular transformation, or in the a-component. (Note that the present theoretical system could be expressed in terms of stimulus sampling models such as that of Estes (1972) or Bjork and Murray (1977)).

Perceptual concepts. Perceptual concepts such as the Gestalt concept of closure, Garner's (1974) concept of integrality, and the general topic of pattern recognizers have always been applied to the most primitive form of the stimulus. It may that this is appropriate although at least some Gestalt concepts have been assumed to result from inferential processes by their opponents. Within the present context it would be worth asking whether or not such concepts can be identified as operations of a particular kind of transformation, and, therefore, whether or not they should be given a locus strictly in the a-function.

One difficulty with our theory is that stimulus transformations are covert mental operations. Thus, when we said above that in the choice reaction time task, the subject makes a transformation from a stimulus code to a name code, we were depending upon our intuition as a means for selecting the mental

operation. Within limits such intuitions come easily which, of course, does not speak to validity, but does suggest that investigators may agree to some extent. Clearly, what is needed are experimental methods which define the kinds of transformations, the errors associated with them, and the time that they require. Fortunately, there is hope of achieving that kind of objectivity. One possibility is suggested by an experimental paradigm presented by Tulving and Watkins (1975) for the identification of specific units in stored feature codes. It would seem that a careful deployment of that technique could extend it to the analysis of other kinds of codes.

Capacity

An important question about any system concerns the limits or capacity of the system. The question of the information processing limits of human performance has traditionally been approached by two divergent lines of investigation. One of these is associated with complex tasks in which the operator is presented with multiple stimuli which require multiple responses. This research is concerned with the concept of the system as having a limited "capacity" for information processing and response capabilities. The second line of investigation involves selective or focused "attention" in which the operator is presented with two or more sources of information presented simultaneously and is required to respond on a limited portion of that information.

The concept of the "capacity" of a system has traditionally been a concept reserved for serial systems as compared to parallel systems. This limitation of the term was an oversight in early research as "capacity" has proven to be an equally important concept for parallel systems as it has been for serial systems as we will discuss below. In any case, in studying system capacity, investigators appear to be using the term "capacity" with three different meanings without distinction. The first is a structural meaning of the term

which expresses "capacity" as the volume of a container. The usual metaphor is the number of stimulus items that can be held in short-term memory at one time or the maximum stimulus set that can be used (e.g., Miller, 1956; and most everyone since). According to this view, the small size of the immediate memory span reflects the limiting content of short-term memory. It is interesting to find this structural concept at the heart of so many proposals which purport to be functional or process theories. As indicated in our discussion of the a-component and STS, this limitation or loss of material from the icon to short-term memory can result from process limits without recourse to a volume or content postulate.

Another type of structural limitation which has been postulated is the previously mentioned single channel theory. Single channel theory (originally formulated by Welford, see Welford, 1968; Kantowitz, 1974; Kerr, 1973; Senders, 1970) first arose in response to the need for a theory to explain the psychological refractory period and related phenomena, all of which have in common that several stimuli call for more than one response. The prototypic finding is that if two stimuli occur close together in time, then the response to the second is delayed. Kantowitz (1974) presents an extensive review of the literature in this field. Single channel theory holds that man's central decision mechanism is capable of dealing with only one decision at a time; if a situation demands two or more simultaneous or closely successive decisions, as in the double stimulation paradigm, then one response, usually the second, will be delayed. Most versions of the theory also specify that the channel has a fixed capacity and that the locus of the bottleneck is at the response selection stage of information processing (see Smith, 1968, for a discussion of processing stages in choice reaction time, or Teichner, 1974, for a more thoroughly developed discussion of stages).

A number of weaknesses have prompted the search for alternatives to the single-channel theory. Kerr (1973) mentions as among these, the finding that after long practice, decision time in a choice reaction time experiment becomes independent of the number of stimuli. This is a particularly disturbing finding for a single-channel theory which places the locus of the processing bottleneck at response selection. Another difficulty is that contrary to the predictions of the theory, people can, in some cases, perform tasks in parallel, in the sense that total time for simultaneous performance is less than times for both individual tasks combined (Kahneman, 1970).

Allport, Antonis and Reynolds (1972) present an attack on the single-channel theory which is based upon the observation that subjects can simultaneously shadow speech (repeat aloud verbal material presented by earphone, as it is presented) and either take in (but not overtly respond to) complex visual stimuli or sight read music at the piano. This finding is clearly a challenge for any single channel theory of dual task performance. Allport et al., however, do not dwell on single-channel theory's emphasis on response selection, and shadowing is a skill in which response selection is not a major factor.

A second view of "capacity" ahs the flavor of a limitation on content but may be described as the application of the laws of conservation of energy to the question of capacity. According to this view, the individual has a limited quantity of effort (e.g., Kahneman, 1973) or energy (Fechner, 1860) available for distribution among those external demands to which he wishes to respond. Response processes, either covert or overt, to these external stimuli draw from this centralized source. If stimulus demand is low, capacity can be divided successfully. If the stimulus demands exceed this capacity, it cannot be divided successfully and interference occurs. Interference from this point of

view is nonspecific and depends upon the total stimulus demands placed on the system's limited capacity, rather than results from specific subtasks or processes occurring within the tasks. These theories do not always view the capacity of a system or the policy for the attentional allocation as a constant. The actual amount of resources available as well as the assignment of different amounts of capacity to different tasks is influenced by internal and external factors such as task demands, instructions, past experience and the subject's state of arousal (Kahneman, 1973; Moray, 1959, 1969, 1975). The total capacity which is supplied to a task increases with the demands of a task, but in a negatively accelerated way. All aspects of all tasks are presumed to demand processing capacity (Kahneman, 1973), and thus, any two tasks should interfere to some extent, not only if they compete for response selection processes.

These capacity allocation theories have led to the use of the dual task paradigm as a way to evaluate the allocation of attention (effort, energy, direction) and to determine when, and at what task demands, capacity is exceeded. The fundamental notion of the dual task method is that very few tasks require a per son to use all of his mental capacity. If we ask him to do another task simultaneously, we can, by choosing the task appropriately, require more capacity than he is able to provide. If the performance on the first task is not degraded, then an appropriate measure of performance on the second task will be related to the amount of capacity which the first task demands. As usually applied, the subject is presented with a task which requires more or less continuous processing such as a tracking task. In that context, he is presented with an infrequent signal to which he makes a simple detection response. The reaction time to the infrequent signal tends to remain constant until the demand level of the tracking task (or other stimulus demands) reaches

some level after which the reaction time becomes longer. The level at which the reaction time increases is said to reflect the capacity of the subject.

The dual task method has been widely researched and reviews of this research are available (e.g., Kantowitz, 1974; Rolfe, 1971). The most significant earlier review of the dual task methods is that of Rolfe (1971). Rolfe briefly reviews the theoretical basis of dual task methods, the problems associated with the use of the method, and discusses the applied areas in which they have been used with success. Three weaknesses in the dual task method were pointed out by Rolfe. First, poor experimental procedures have diluted the potential worth of otherwise useful studies. The two main problems with experimental procedures have been ambiguity about which task is primary and which secondary, and the lack of appropriate task measurements. The second, and more serious in the long run, criticism is that the vast majority of studies have been carried out in the laboratory, and have not been validated in the field. Rolfe concludes ominously that this lack may mean the technique is reliable, but not valid. The question of field studies in general was the topic of a special issued of Human Factors; see Johnson and Baker (1974) for an introduction to the topic; other articles in the same journal may be helpful. The final criticism is that the secondary task, contrary to the assumptions of the methodology, does in fact, interfere with the primary task. At the least it adds stress to the task situation, and at the most it diverts resources from the primary task instead of simply using unallocated resources. Rolfe concludes with the warning that the secondary task must never replace adequate measurement of primary task performance. It is at best a way of gathering information to supplement primary task information. In spite of these criticisms, Rolfe's (1971) conclusion, based on a large sample of studies, mostly from the decade of the sixties is, "it would appear that the technique is a sensitive indicant of primary task demand when perceptual-motor activity makes up the demand," (p. 144).

One problem not mentioned by Rolfe which reflects on the dual task method and the capacity model which it is designed to evaluate is that not all tasks show a decrement in performance when they are placed in combination. For example, Posner and Boies (1971) found that the interfering effects of a stimulus probe presented during a letter matching task were dependent upon which point in processing that the probe was presented. Results such as this are difficult to explain if one assumes that all processing requires capacity. Capacity models have therefore tended to suggest that early perceptual and encoding stages of human information processing do not demand those resources called "capacity." There is an increasing emphasis in these theories being placed upon the attentional demands of the response selection operation with those processes occurring before response selection appearing to require no "capacity" allocation.

While some research indicates that some stages of human information processing do not demand "capacity" (e.g., Posner & Boies, 1971; Posner & Klein, 1973; Warren, 1972; Conrad, 1972) other recent research indicates that the task itself may not compel the operator to allocate a given amount of "capacity" (e.g., Kantowitz, 1974; Martin & Ogden, 1979). For example, Martin and Ogden (1979) have reported experiments in which dual task memory load effects were eliminated by manipulating the sequencing of stimulus presentations (random vs. blocked) and event expectancies. Apparently the operator must decide in advance, based upon knowledge of the task, how much of his resources to allocate to it. Findings of Martin and Ogden indicate that if the demands of a task are not known to a subject in advance of the task onset, then the results of presenting a secondary task will not be meaningfully related to the difficulty of the primary task. These findings hold in tasks which are sufficiently short in their duration so that the operator cannot adjust his capacity allocation during the course of the task.

A variation of the global capacity model which can handle the above discrepant information is one in which capacity is decomposed or is viewed as a function of stages of processing. While some researchers view these stage models as fundamentally different from single channel or variable allocation models, others see them as only a more precise specification of earlier theoretical models. As these models tend to view capacity as content- or energy-limited, we will discuss them in conjunction with variable allocation models.

The stages of processing models divide information processing into separate stages and have made attempts to isolate the capacity demands of various stages of processing (e.g., Kerr, 1973; Posner & Boies, 1971). Kerr, in her 1973 review, points out that the isolation of capacity demands of different processing stages requires more precise experimental control and detailed analysis of response characteristics than do experiments which are directed toward accessing the global capacity requirements of a task. Within the general area of mental operations, she cited evidence suggesting the existence of the separate processes of encoding, multiple input, rehearsal, transformation, and responding. This evidence for separate processes along with the previously cited research on the lack of dual task interference suggests the importance of considering capacity as a function of stages of processing.

The third view of capacity, the one espoused by our theory, relates capacity to the process limitations of the system rather than the structural or content limitations. Following the standard use of the term in information theory (Shannon, 1962), capacity is viewed as the maximum rate at which information can be processed through the system. This definition of capacity is functional rather than structural. A functional definition has an advantage over structural defintions by providing a measurable limit of information processing. In fact, if a structural limit was all that was implied by capacity,

the number of items that could be processed in a fixed time period would be indefinitely large if the processing rate were sufficiently large.

Applying this functional definition of capacity within our theory, the limits of the system are set in terms of the rate at which information passes through the system and the amount of time the information is available to be processed. If it is assumed that S-S and S-R translations are performed in a serial manner, the rate at which information can pass through the system is dependent upon the number of successive translations through which it must pass; i.e., the more translations the slower the processing of the stimulus. The maximum processing rate or capacity of the system can be no greater than the rate of the slowest translation or process which is involved. Furthermore, in a single channel system, the capacity or rate must decrease for each additional stage of processing involved. Thus, tasks which required fewer translations than others can be accomplished more quickly and with fewer opportunities for error.

There are no necessary bounds on the number of conceivable successive S-S translations, nor on the size of the M:S sets except that obviously, they cannot exceed what has been learned. Yet it is well established that the number of items that can be assimilated, i.e., the memory span, is very limited. Suppose that all translations had to be completed while the stimulus item(s) remained in STS. If the stimulus remained there without loss until it were somehow erased, the size of the stimulus set and the number of successive transformations could be indefinitely large. But, as we and everyone else assumes, the stimulus has a limited persistence; it decays as a function of time since initial representation. Accordingly, if all translations must be completed before the stimuli in STS are reduced to noise, the number of transformations in M:S and the size of the stimulus sets there must be limited.

That limitation necessarily depends upon the rates at which the various translations can be made and that in turn upon the complexity of the codes (length and amount of information in the code), possibly the qualitative characteristics of the codes (feature coding might or might not be faster than name coding at equal informational levels), the number of items in the stimuli simultaneously present in STS, and the amount of information in those items. Clearly, for a limited duration in STS, it is to the advantage of the system to minimize the number of translations and the size of the stimulus set in M:S. It can be hypothesized that as the number of items in STS increases from 4 to 6, not only will the number of items that can be produced in immediate recall decrease (Teichner, 1979 in press; Teichner, Reilly & Sadler, 1961), but (1) the number of transformations of the stimulus which can be made will decrease, and (2) the size of the stimulus set that can be used will decrease. The decrease in any case will be to some limit which will approximate the conventional memory span for STS-S_1-S_2 where S_1-S_2 is a translation from a feature code to a name code.

The concept of erasure rather than decay from STS can also be made consistent with the above expectations by assuming that each item in STS remains there until STS-S_1 has been completed, and then that it is abolished and an S_1 trace is established. In turn, the S_1 trace may be erased by S_2, etc. To be consistent with the limited persistence hypotheses, this model must require that the M:S representations have a limited persistence, and this is consistent with most models of active working memory. On the face of it, both models appear equally good in the absence of experimental testing. The single trace model which assumes a limited STS trace has the advantage of allowing the individual to be able to recall what is in STS by reinspection, even after all transformations are completed, as long as the trace remains. However, that

could also be accomplished by the successive trace model if successive decodings were permitted which in effect reversed the translation sequence. That model has the advantage of allowing reinspections of the last translation prior to any particular translation whereas the first model would require that a translation not be inspected, but that the whole sequence be repeated. These two kinds of recall differences seem testable with latency measures. Note that in both cases the inspection problem would be solved if the occurrence of a translation provided something more lasting to LTM which could then be called upon for inspection. This is not unlike the rehearsal buffer in STS proposed by Atkinson and Shiffrin (1971), but we have already rejected this concept. In any case, as a working approach, we have assumed a decaying trace in STS and that it is this in conjunction with the maximum processing rates achievable in the S-S translation which limits memory capacity.

We now propose a model of the decaying STS as a working hypothesis. All of the stimuli presented through a series of outputs from psychological moments can be thought of as a series of temporally defined compartments within STS. Everything within a single compartment is defined as simultaneous in time in terms of stimulus messages with feature-defined symbols. The number of compartments that can be present at one time has a limit, but under normal conditions the decay rate will be such as to prevent that limit from being reached. However, under conditions of high activation, the scanning rate could increase to a level that might not be offset by the decay rate. This would be observed as performance on the decreasing side of the inverted U-shaped arousal curve.

We shall assume that the amount of information stored in STS at any one time depends upon (1) the rate of input to STS which in turn depends upon the period of the scanner and the response criterion of stimuli encountered during a given period, (2) the total amount of information accumulated in STS, and (3)

the decay rate. By storage we mean the aggregate of all compartments, stimuli, and features which have value on a coding dimension.

Previous stimulus trace models (e.g., Bower, 1977; Wickelgren, 1970) have assumed that the decay rate is an exponential function of time and have not considered the amount stored. These models have not been fruitful. It is likely, though, that the rate of loss depends upon the amount of storage at least within one temporal compartment. Therefore, we shall assume that the rate of loss (R_L) is proportional to the number of features present in aggregate in one temporal compartment and, therefore, that it could vary from compartment to compartment as the amount of storage in each compartment varied. Therefore, the rate of change is exponential, or

$$R_L = \frac{dN}{dt} = -CN \tag{10}$$

where N is the number of features in a compartment and C is the rate constant. Note that the same model could apply if the loss were assumed proportional to the total storage of any or all kinds in STS.

By necessity, our theory must acknowledge some structural limitations in human information processing as well as the functional limitations discussed thus far. These limitations affect the rate or capacity of the system in a somewhat peripheral manner. From our point of view, structural limitation would occur whenever two tasks place incompatible or excessive demands upon the mechanical aspects of the perceptual or response systems. For example, an operator cannot simultaneously acquire two visual stimuli which are separated by a space greater than that which is accessible by the peripheral vision of the eyes, nor can he simultaneously make two different verbal responses. Our recognition of this sort of structural limitation is not unique as numerous other researchers have pointed to these structural incompatibilities (Kahneman, 1973; Kerr, 1973; Shallice, 1972).

As indicated previously, a second aspect of system limitation involves "selective attention." Given a limited capacity system there is a need to explain how the system selects from available stimuli those which are to receive further processing and those which will not be processed further. In addition, the consequences of this selectivity in terms of processing rate and accuracy must be addressed. The existence of some sort of selective process in human information processing has been well established in many experimental paradigms (e.g., Bamber, 1969; Deutsch & Deutsch, 1963; Egeth, 1967; Treisman, 1969; Welford, 1968). In a series of tasks with multiple auditory stimuli, Cherry (1953) found that when messages were directed to separate ears, some rather drastic changes in the nonselected ear or channel went unnoticed by the subject. They did not notice when the language spoken in the nonattended message switched from English to German or when the recorded message was reversed and played backward. Not all of the task irrelevant information is disregarded by the system as Cherry's subjects did notice when the irrelevant message switched from a male voice to a tone or a female voice. Similarly, in another auditory shadowing experiment (Treisman, 1960) subjects were found to switch from the irrelevant stimulus message when it made contextual sense to do so. Other research in the visual realm indicates that subjects can selectively respond to specific dimensions in multiple dimension stimuli but that the presentation of certain types of irrelevant visual information to the system may either enhance or interfere with performance (e.g., Dyer, 1973; Garner, 1974).

Although there have been many attempts to model the attentional process the nature of this selective process and the interaction of multiple stimulus elements is still unresolved. Some models have placed the locus of selective processes in encoding or perceptual mechanisms (e.g., Broadbent, 1958, 1971;

Treisman, 1969) with some sort of filter operating to screen out or attenuate task-irrelevant information. Other researchers have postulated multichannel or unlimited capacity in perceptual processing with all sensory inputs which impinge upon the organism being perceptually analyzed to the highest level. According to these theories, selectivity (attention) takes place later in the system in the stages of STS or response production. Researchers such as Sperling (1960), Atkinson and Shiffrin (1968) and Shiffrin and Geisler (1973) have located the selective process at the point of information transfer from a high capacity (structural or content) nonselective sensory store into a limited capacity in STS. Deutsch and Deutsch (1963) have postulated central structures which preset the weighting importance of stimuli. For a stimulus to be selected for response it must exceed a threshold value. The ranking of importance of a stimulus and its threshold are determined by the operator's level of arousal based upon physiological and incoming environmental stimuli.

Most early theories of selective attention have focused upon a single locus for the attentional process. Selective attention, however, need not operate at a single stage of processing and, depending upon where it operates, it may have significant effects upon later stages. In a review of the effects of perceptual sets, Haber (1966) concluded that selective attention was a function of perceptual processes as well as response production. Other researchers (Posner, Klein, Summers & Buggie, 1973) have similarly suggested that set affects both the early acquisition of information and the operation of later decision making mechanisms. Finally, some researchers (Erdelyi, 1974; Gibson, 1976) have hypothesized that all phases of information processing from the initial perceptual phase to the later response phases involve some form of selectivity. The present theory postulates attentional mechanisms in perception, memory, and at the point of response.

While the presence of some forms of task-irrelevant information can produce interference in terms of errors and time to complete a task relevant to the absences of such information. Other information may actually serve to enhance performance (Garner, 1976; Dyer, 1973; Redding & Gerjets, 1977). The theoretical mechanisms used to explain stimulus and response selectivity and irrelevant stimulus interference should be able to account for irrelevant stimulus enhancement as well.

As indicated in an earlier section, our model views selective attention as beginning with stimulus acquisition in the a-component. Stimuli are selectively perceived and processed based upon the level of the response criteria (RC) for these and other stimuli in the environment and the rate of the perceptual scanner. As suggested before, the RC is the criteria for the amount of stimulus evidence (neural impulses) which must build up before a stimulus enters STS. Stimuli do not enter STS nor receive further cognitive processing until they reach their RC. Once a stimulus reaches RC it is placed in STS along with all other stimuli which have surpassed their RC in that same perceptual moment (see The Whole a-component). Priority for further cognitive processing in terms of S-S and S-R translations is based upon the arrival of stimuli within STS. Stimuli arriving in earlier scanning periods or moments are processed prior to the processing of stimuli from later scans. As the RC is viewed as varying from trial-to-trial within a task and as being dependent upon instructions, stimulus probability, learning, and motivational factors, etc., it is reasonable to assume that central events such as task-relevant stimuli and stimuli with high probabilities of occurrence or motivational value would have lower RCs than peripheral events of low task relevance. Due to their lower response criteria, central events would probably enter the system in an earlier perceptual moment and be "selectively" processed before peripheral

events. Peripheral events would tend to become lost (fail to reach their response criteria) or be delayed in processing (fall into later perceptual moments). In addition, perceptual selectivity is indirectly related to stimulus energy as the level of stimulus energy determines the rate of neural transmission or the rate at which perceptual energy is acquired and its duration (Efron, 1973; Engle, 1970; Pieron, 1939). High intensity stimuli build up their neural impulses at a faster rate than low intensity stimuli. If two stimuli having the same RC were presented to the system at the same time, the more intense stimulus would reach its response criterion first and would begin higher level processing prior to the low intensity stimulus. Thus, perceptual selectivity as well as selectivity of processing within STS is dependent upon the setting of the response criterion, the rate of the perceptual scan, and stimulus intensity.

From the above discussion, it should be clear that not all irrelevant stimulus information is eliminated during perceptual processing. However, previous research on selective attention indicates that subjects presented with task-irrelevant information are capable of preventing responses to these stimuli while responding correctly to task-relevant stimuli (e.g., Dyer, 1973). Given some higher level processing of irrelevant information, but relatively few responses to these stimuli, it is necessary to postulate a selective mechanism beyond the perceptual stage. Further selectivity of stimuli for response occurs within M:S and M:SR. Generally the selection of which stimuli or stimulus features belong to the categories of relevant or irrelevant information can be determined within M:S as previously described. M:S consists of relevant (positive) and irrelevant (negative) transformation sets, and items in STS are identified in terms of which pre-established set it belongs. Once it has been determined whether an item is a member of the relevant or irrelevant

set and all S-S translations are complete, it passes into the S-R translation stage.

As can be seen in Figure 2, there is a portion of long-term memory associated with response processes, LTM:S-R. This portion includes the ability to locate and organize response codes to be paired with stimuli following S-S translation. This pairing of response codes with the stimuli leads to the selection of a motor paradigm and response execution. This portion of long-term memory operates in conjunction with M:S to insure that M:SR contains those response codes necessary for the S-R translations to lead to the selection of an appropriate motor program. It is at the point of M:SR that the system makes a decision as to whether a stimulus will be processed to the point of response. If the transformed stimuli match the subset of stimulus events identified as irrelevant, it is paired with a response code of "no response" and no further motor program or response is initiated. Stimuli which match those designated as relevant undergo an S-R translation which will lead to the selection of a motor program and response initiation.

Having explained the means by which the system selectively perceives and selectively responds to information it is still necessary to explain the interference or facilitation which often accompanies the presence of task-irrelevant stimuli. Whether interference or facilitation results from the addition of stimulus information to that which is initially present in the task is a complex issue. Facilitation or interference effects are determined by the level of correlation of new stimulus elements with the intial task-relevant elements and by interactions among different types of dimensions. See Garner (1974, 1976) and Garner and Felfoldy (1970) for an excellent coverage of the effects of these variables.

Facilitation from new information may result in one of three ways. 1) If the new stimulus information is redundant or highly correlated with the initial task-relevant information, it will be come associated as a function of experience with the same response code and motor programs in M:S-R. Once both stimulus elements are associated with the same motor program, the element which is processed to M:S-R first will result in response execution. New stimulus information which is higher in intensity than the initial stimulus information has a lower RC, or which requires fewer S-Rs will be processed in a shorter period of time than the initial information and will produce facilitation. A small amount of facilitation may occur even if the new stimulus is identical in RC, S-S translations,and intensity. This is due to the normal distribution of RC and variation occurring from trial-to-trial. 2) Facilitation may also occur by priming of the S-S translation. It is reasonable to assume that the speed at which an S-S translation can occur is dependent upon past experience with the S-S translation relative to other S-S translations. If S-S translations are hierarchically ordered based on the probability and the recency of their use, then initiation of an S-S translation should raise it in the heirarchy of possible translations, thereby increasing the speed with which it may be accomplished. If the new stimulus information is uncorrelated or nonredundant but has S-S translations in common with the initial task information, it will produce facilitation if it enters the system at an earlier perceptual moment than the initial task information. By executing the common S-S translation in close approximation but prior to its execution by the initial stimulus information, the translation is primed and occurs more quickly than it would if it were not primed. 3) Finally, facilitation may occur by the priming of S-R translations and their associated motor programs. This priming would occur in essentially the same manner as suggested for S-S translations.

Interference from new irrelevant stimulus information will only result when the new information is not redundant or not consistently correlated with the relevant stimulus information. This interference may result from one of two mechanisms. 1) The introduction of new stimulus information may produce interference through negative priming of S-S translations. If the new information enters the system prior to the original information and has no S-S translations in common with it, it will serve to prime S-S translations other than the ones relevant for the task. This priming in turn will lower the hierarchical position of the relevant S-S translation causing it to take longer than if the irrelevant information were not present. 2) If the irrelevant information enters the system in an earlier perceptual moment than the relevant information and results in an S-R translation different from the translation which will be required by the task-relevant information it may also produce interference. This interference will result from negative priming similar to that for negative priming interference in the S-S translation stage. Additional interference at this stage will occur if, upon completion of S-S translations, the irrelevant stimulus information results in an S-R translation different from the relevant stimulus occurring on the trial in question but included in the set of S-R translations associated with potentially relevant stimuli. In this case the subject will either make an incorrect response or will be required to block that response in order to make a response to the relevant stimulus. The blocking of the response implies at least some of the most recent S-S translations are simultaneously available in order to provide the operator with a basis for going back to the S-S translation and assigning the stimulus to the irrelevant "no response required" stimulus set.

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SECTION B

TR-79-3 Response Criterion Model for the _a_-Component of the Information Processing Theory of Human Performance

George Ekel and Warren H. Teichner

TR-79-4 Compression of Stimulus Information in an Information-Seeking Task

Evelyn Williams and Warren H. Teichner

TR-79-5 Information Processing of Different Stimulus-Response Levels in Identification and Classification Tasks

Evelyn Williams and Warren H. Teichner

TR-79-6 On the Relation Between the Judgmental Tasks of Temporal Order and Fusion

Gregory M. Corso

RESPONSE CRITERION MODEL FOR THE a-COMPONENT OF THE INFORMATION PROCESSING THEORY OF HUMAN PERFORMANCE[1.]

George Ekel and Warren H. Teichner

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The first element of the Information Processing Theory of Human Performance, developed by Teichner (Teichner, 1974; Teichner & Krebs, 1974) and described earlier in this report, is the _a_-component.[2.]

_A_-component of human performance includes all these neural and psychological processes involved in the preliminary processing of sensory input. They may be divided into two classes:

a_k - neural transmission of sensory information, and

a_s - encoding of sensory information (stimulus encoding).

Two measures of these processes relevant to the overall human performance are their speed (the time required for their completion) and accuracy (most conveniently measured by the amount of information transmitted).

The part of the human information processing system represented by the _a_-component is a serial system. That is, a_s begins only after a_k has been completed. Therefore, the time consumed by the _a_-component of information processing is an arithmetic sum of the time it takes for a_k and a_s to be completed:

$$T(a) = T(a_k) + T(a_s). \tag{1}$$

The total amount of information transmitted through a serial system cannot exceed the smallest amount transmitted through any of its components:

$$I(a) = \min[I(a_k), I(a_s)]. \tag{2}$$

Practically, however, the neural transmission component, a_k, has little input (compared to the a_s component) to the time taken by, and the amount of information transmitted in, the _a_-stage of information processing. That is, for the same neural path (the same sensory organ and the same effector used in

tasks varying in other respects, e.g., pushing buttons with a finger in response to a visual signal), the variability of time consumed by a_k is negligible in comparison to the variability of time consumed by a_s, and that goes for both random variability and variability due to independent variables usually considered relevant for information processing tasks. Also the amount of time consumed is small compared to the total time consumed in an information processing task of any complexity. It has been customary then, to consider $T(a_k)$ as a constant and estimate it by the round figure of 100 msec. Likewise, losses in the amount of information transmitted, both their general level and the variability incurred in a_k, can be considered negligibly small compared to those associated with a_s. Therefore, the main focus of interest in developing and testin the a-component of the general information processing theory of human performance is a_s, stimulus encoding. From now on, then, to avoid subscripts, the a-component will be understood as stimulus encoding unless a distinction between a_k and a_s is specifically made.

A successful model for the a-component should be able to account for differences in time and accuracy of human performance both in various information processing tasks (detection vs. classification vs. identification) and, with signals conveying various amounts of information.

The a-component model which has been proposed is a response criterion (RC) model. Several RC models have been proposed in the literature. Probably the first such model was the one proposed by Stone (1960), further developed by Edwards (1965), and used by Fitts (1966) to account for speed/accuracy trade-offs in choice reaction time experiments. The model, called stimulus-sampling-and-decision model, assumed that (a) an RC, different for each response, is established in terms of the probability of one response, R_i, vs. other responses based on relative payoffs for speed and accuracy, (b) stimulus

presentation triggers a flow of sensory evidence constantly changing the probability of various responses being correct; and (c) a neural mechanism samples the evidence, computes the probability, and as soon as the probability for one response exceeds its RC, the response is triggered.

Another RC model has been proposed by McGill (1961, 1962, 1963) and developed further by McGill and Gibbon (1965). McGill's stochastic latency model was intended to account for the relationship between stimulus intensity and simple reaction time. The model assumed a fixed RC (an impulse counter) and a randomly variable neural impulse rate as a function of stimulus intensity: the more intensive the stimulus, the higher the impulse rate, the sooner the impulse count reaches RC, and the shorter the reaction time.

Grice (1968), accepting the basic mathematics of McGill's model, questioned his assumption of a fixed RC and variable impulse rate. On both empirical and theoretical grounds Grice argued that a more plausible assumption is the reverse: to consider the neural impulse rate as fixed (for repeated presentation of the same stimulus in the same experimental conditions) and the RC as variable, fluctuating randomly around some mean value. In later papers (Grice, 1971, 1972a, 1972b; Grice et al., 1974, 1977, 1979 in press), Grice, together with his associates, made some changes in the original model, developed it in more detail, and successfully applied it to stimulus intensity effects on differential eyelid conditioning, simple reaction time, and choice reaction time. Teichner and Krebs (1972) applied Grice's variable RC model to explain the relationship between simple reaction time to visual stimuli and their luminance.

The RC model for the _a_-component of the theory is the one proposed by Grice (1968 and later studies) and used by Teichner and Krebs (1972) for visual simple reaction time. The model (see Figure 1) states that there are two variables determining stimulus encoding time, and consequently reaction time: (a) the rate of accumulation of sensory evidence and, (b) the RC level.

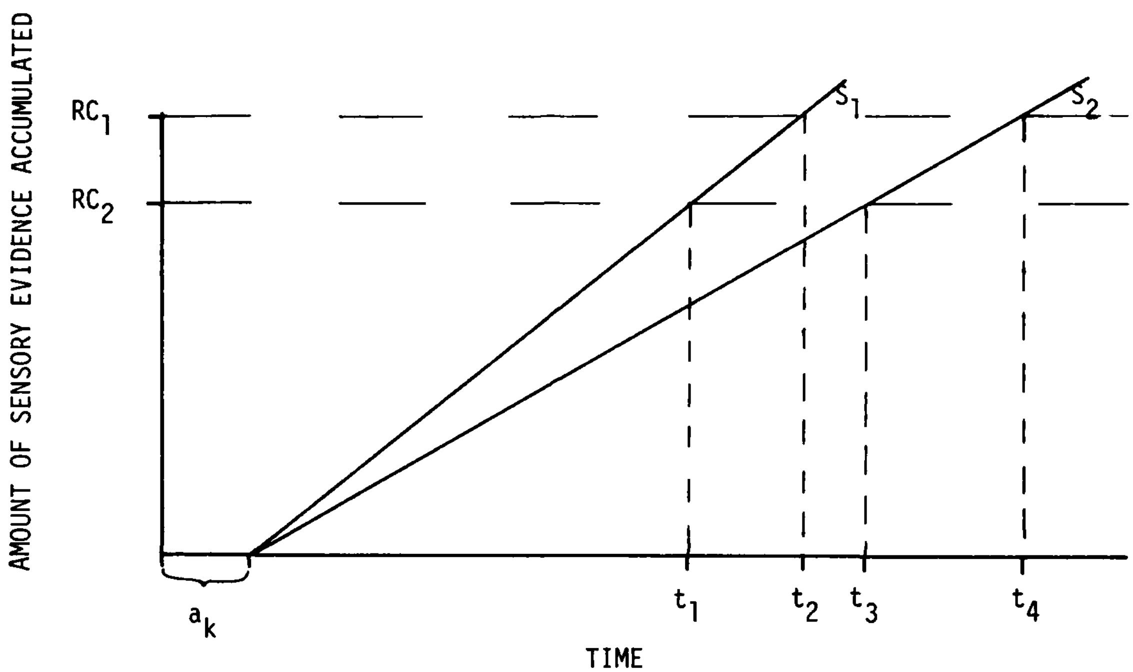

Figure 1. Diagram of Response Criterion (RC) model. Two different RCs (RC_1 and RC_2), such as might be associated with different tasks or different speed/accuracy requirements, are presented. Two simultaneously presented stimuli, S_1 and S_2, are presented with different slopes indicating differences in the rate of accumulation of sensory evidence. Stimulus encoding time and, consequently, reaction time for these stimuli is dependent upon when the accumulation of sensory evidence related to the specific stimulus reaches the RC associated with the task in question, either t_1, t_2, t_3, or t_4. Neural transmission time, a_k, is considered a constant and independent of both RC and the rate of accumulation of sensory evidence.

The faster the sensory evidence accumulation rate, the sooner the stimulus encoding will be accomplished and the shorter the reaction time will be. On the other hand, the lower the RC, the sooner it will be reached by the accumulating evidence, and the shorter the reaction time will be.

Grice and his associates demonstrated effects of a number of variables on the RC level. Effects of catch trials on reaction time can be interpreted in terms of RC adjustments (Grice, 1972b; Grice et al., 1974; Grice et al., 1976), and so can the effects of stimulus similarity (Grice et al., 1979 in press). Beck's (1963) data on eyelid conditioning and Grice and Hunter's (1964) data on eyelid conditioning and simple reaction time, analyzed in terms of RC model by Grice (1968) show that effects of the subject's exposure to various stimulus intensities can be interpreted as affecting the subject's RC level. When exposed to only one stimulus intensity the subject sets his RC at that intensity; on the other hand, exposure to various stimulus intensities results in an RC somewhere between stimulus levels which makes his reaction times to a low-intensity stimulus slower and to the high-intensity stimulus faster than if these stimuli were presented separately. Adaptation to various stimulus intensities can be interpreted as changes in RC level (Murray & Kohfeld, 1965; Kohfeld, 1968). Longer reaction times have been found after adaptation to high-intensity stimuli than after low-intensity stimuli adaptation. Warning signal intensity has been found to have a similar effect on RC level: reaction times after high-intensity warning signals were slower than after low-intensity warning signals (Kohfeld, 1969a, 1969b). The proportion of high- and low-intensity stimuli in an experimental session affects the RC level: the greater the number of high-intensity stimuli the slower the reaction times (Murray, 1970).

The Teichner model would explain these stimulus intensity effects in terms of activation. Adaptation of the operator by exposure to high-intensity stimuli or the presentation of a high-intensity warning signal would raise the level of activation in the system. An increase in the level of activation would act to change the RC level and, in addition, it would act to change the rate of scanning by the central timing mechanism. This would cause subsequently presented stimuli to reach their RC and to begin higher level processing within an earlier psychological moment than if the preadaptation had not occurred. For a further discussion of the temporal scanning mechanism see Teichner and Williams (1979, Section A--"The Whole a-Component").

From the point of view of Teichner's Information Processing Theory of Human Performance, it was important to decide if the three kinds of information processing--detection, classification, and identification--require an assumption of a separate stage in processing after the stimulus encoding stage, or if they can be adequately explained by the RC model in the a-component of the theory.

Detection, classification and, identification require successively more sensory information processing for successful completion of the task. It can be hypothesized that the difference between these three tasks will be reflected in different RC levels. In detection, where the amount of sensory information necessary for response is the smallest, RC would be set at the lowest level. In identification, where the greatest amount of sensory information has to be processed, RC would be set at the highest level. For classification, with an intermediate amount of information required, RC would be set somewhere between the other two RCs (see Figure 2). The results obtained by Grice, Hunt, Kushner and Morrow (1974) and by Grice, Nullmeyer and Spiker (1977) provide indications that this hypothesis may be supported. Their analyses showed that speed/accuracy trade-off (manipulated by instruction) can be accounted for by appropriate

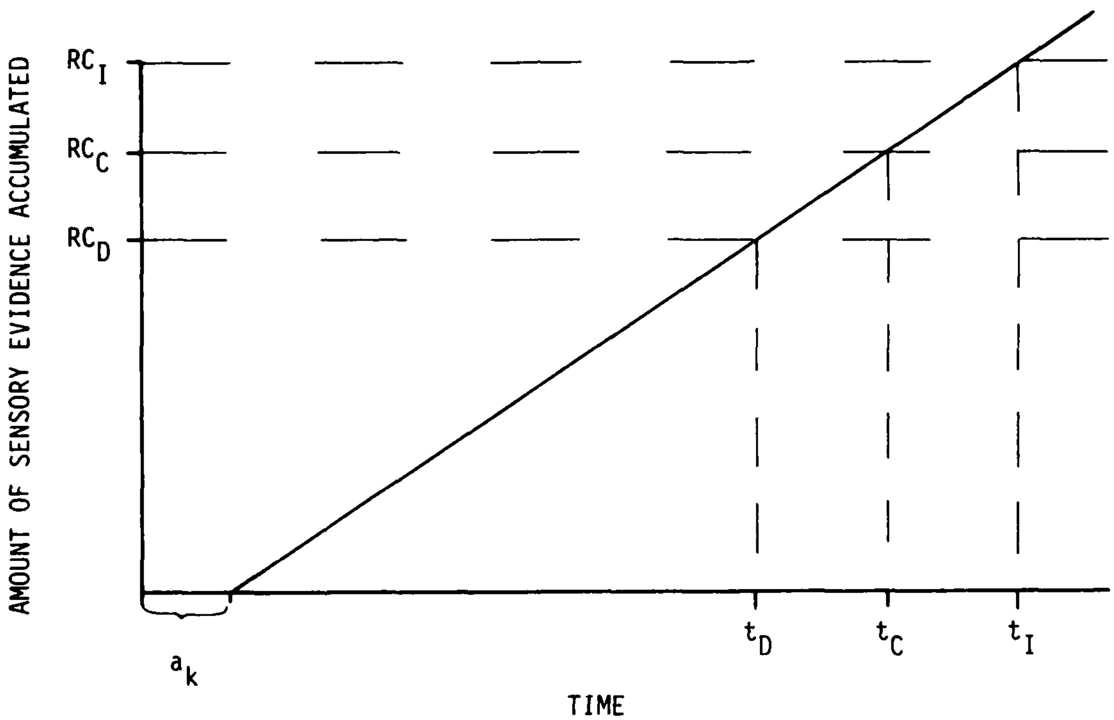

Figure 2. A possible response criterion interpretation of differences in the response times in detection (t_D), classification (t_C), and identification (t_I) tasks for the same stimulus in terms of different response criteria for the three tasks, RC_D, RC_C, and RC_I.

adjustment in RC level from one experimental condition to another. To test this hypothesis, the three tasks were used in the experiment; detection, classification and, identification.

Information processing in detection, classification and, identification tasks also depends on specifics of the task, in particular on the stimulus set, S-R compatibility, and on the type of classification required. For example, in a very simple identification task, with high S-R compatibility where subjects held their fingers on buttons and had to respond to the button vibration with the finger on the vibrating button, choice reaction time approached simple reaction time, or--as it may be rephrased--identification became detection (Leonard, 1959). Mowbray and Rhoades (1959) have shown in choice reaction time experiments with thousands of trials, that increased practice has a similar effect. Effects of the type of classification required on the response time have been demonstrated experimentally by Morin, Forrin and Archer (1961) and by Fitts and Biederman (1965), and analyzed theoretically by Posner (1962, 1964). In the experiment conducted by Morin, Forrin and Archer, and replicated by Fitts and Biederman, subjects had to respond to four stimuli: ○, ○○, □, and □□ . The stimuli in this set varied on two dimensions, shape and number, and each of these dimensions had two values, the shape may have been either a circle or a square and there may have been either one or two figures. The subjects were asked either to respond with one response, R_1, to circles and with another response, R_2, to squares, or to respond with R_1 to one circle and two squares, and with R_2 to two circles and one square. In both cases the subjects were performing a classification, or many-to-one translation, task. But the two types of classification differed in an important respect: in the first task the subject could ignore one dimension on which the stimuli differed, while in the second, none of the stimulus dimensions could be ignored. As could

have been expected, it took much longer to perform the second type of classification than the first, even though the amount of information to process was, in both cases, the same. Actually, the first type of classification of the four stimuli was about as fast as identification of two stimuli (Morin et al., 1961), while in one of these experiments (Fitts & Biederman, 1965) the second type of classification took even longer than identification of the four stimuli in which twice as much information had to be processed.

These and other similar findings show that in cases of high S-R compatibility identification may be reduced to detection and classification may be a much more complex task than identification. Should this finding be generally confirmed, classification could be viewed as a separate stage in information processing, while identification and detection may involve the same types of processing and differ only in the RC level adopted for each of the two tasks. This would be especially true for tasks with highly compatible S-R codes.

To test this hypothesis, three different stimulus sets were used: alphanumerics (Symbols), squares with a missing side (Missing) and, single sides of a square (Singles).

Symbols were three letters (E, H, P) and three digits (2, 3, 6), altogether six, with a seventh symbol, digit 8 serving as a mask. Singles were four single sides of a square (⎸, ‾, ⎹, _), and the whole square (□) served as a mask. Missing were four incomplete squares (⊐, ⊔, ⊏, ⊓), with the whole square (□) used as a mask.

In the Detection task the subjects were asked to indicate if any stimuli preceeded the mask or if only the mask was presented. In the Classification task the subjects were given three types of instruction depending upon the stimulus condition used. In the Symbol condition they were to say if a letter or a digit or the mask alone had been presented; with Singles and Missing stimuli,

subjects were to indicate if the single (or Missing) side was on the North-South or on the East-West direction, or if the mask alone was presented. In the Identification task, the response consisted of naming the letter or digit or of naming the location of the Single or Missing square side.

Thus, the Symbol set differed from the other two stimulus sets in that its signals conveyed the most sensory information (six possible Symbols vs. four possible Single or Missing sides of the square). Also, alphanumerics is a well-mastered set of stimuli for literate adults, and naming them or classifying them into letters and digits are tasks of a very high degree of S-R compatibility. On the other hand, categorizing Single and Missing square sides into North-South and East-West directions could have required a more complex process separate from stimulus encoding and might have turned out impossible to be accounted for by adjusting RC level.

Finally, the third variable which was hypothesized to affect stimulus encoding was the stimulus duration. Since a certain amount of sensory information is needed for each of the three tasks examined, stimulus duration, within the range of very short durations, should have an effect on the amount of information transmitted during the stimulus encoding stage of information processing. Moreover, the more information the task requires, the more pronounced this effect should be. Therefore, an interaction was expected between these two variables, tasks and stimulus duration: the least affected by stimulus duration should be the amount of information transmitted in Detection, since the smallest amount of information is needed there, the most affected by stimulus duration should be the amount of information transmitted in Identification, since Identification requires processing the greatest amount of information.

To test this hypothesis four different stimulus durations were used: 10, 20, 30 and, 40 msec.

In summary, three independent variables were selected as relevant to testing the RC model for the a-component of Teichner's theory: task, stimulus set (SS), and stimulus duration (SD), each within the following values:

task - Detection (D), Classification (C), Identification (I);

SS - Symbols (alphanumerics), Single (a single side of a square), Missing (a square with one side missing); and

SD - 10, 20, 30, 40 msec.

These three variables were combined orthogonally so that 3 x 3 x 4 = 24 experimental conditions resulted.

Since some of these variables were expected to affect reaction time, some the amount of information transmitted, and some both; these two measures, reaction time and information transmitted, and a combination of them, information transmission rate, were used as dependent variables.

Method

Four series of experiments were run. Three of them were pilot studies. In the pilot studies, various independent variables considered of possible interest and of possible effectiveness, were tested (e.g., monocular vs. dichoptic stimulus presentation). Also a wide range of values of some variables (e.g., stimulus duration) were tested to determine the critical range and later used in the main experiment. Altogether 123 subjects participated in one or more conditions and series of these pilots studies. The data from these studies are not reported here. Therefore, the subsequent description of the method concerns only the last fourth and last experiment in the series, the results of which are reported in this study.

Subjects

Nine male and female New Mexico State University students served as subjects. Participation in the study was voluntary. For participation the subjects received credit towards a partial fulfillment of their requirements for the Introduction to Psychology class. All subjects were right-handed, English was their primary language and, they had uncorrected "normal" vision (by their statement, the vision was not tested).

Stimuli and Apparatus

The stimuli were presented in a stereoscope with the internal dimensions of 19 x 18 x 66 cm. Four high-quality front surface mirrors were horizontally adjusted to enable proper fusion by subjects of varying inter-pupillary distance. Two seven-segment alphanumeric, light emitting diode (LED) stimulus displays were mounted in the end corners of the scope, 65 cm from the viewer's eyes. The displays, which were 3 x 2 cm and 15 cm apart, resulted in a subtended visual angle of 2.6°.

Interstimulus interval (ISI), stimulus duration (SD) and, intertrial interval (ITI), were all controlled by Lafayette 5002A decade timers (millisecond accuracy). A microphone mounted on the ventral surface of the stereoscope activated a sound detecting relay. The relay controlled a millisecond timer, responsible for measuring subjects' verbal reaction time. A pre-trial warning tone (2000Hz) was delivered by a Hewlett/Packard model 200CR audio occilator.

All timers and the tone generator were interfaced with a scimulus control selector (in-house design) which was used to select stimuli, SD, and ISI. Three sets of stimuli were used: Symbols (alphanumerics), Singles (single side of a square) and, Missing (squares with one side missing). All the stimuli were compositions of the seven LED segments, 8, and consequently, were stylized in straight lines at right-angles.

Symbols included: P, U, H, 2, 3, 6, and 8 as the mask.

Singles included: |, ¯, |, _, and □ as the mask.

Missing included:], ⊔, [, ⊓, and □ as the mask.

The stimuli were presented dichoptically; each stimulus was presented to one eye (once to the left and once to the right). The mask was presented to both eyes.

Design and Procedure

A mixed, within/between subjects design was used in which three subjects were randomly assigned to each of the three tasks--Detection, Classification or, Identification. Within each task, each subject was exposed to all three stimulus sets (Symbols, Singles, Missing), and all four stimulus durations.

Each trial started with a 1-sec auditory warning signal. Immediately after the tone, a stimulus was presented. The stimulus was on for 10, 20, 30, or 40 msec. Immediately after the stimulus or after a 2-msec delay (ISI of 0 or 2 msec), the mask was presented.[3] The mask stayed on for the whole ITI, i.e., for 6 sec, and went off simultaneously with the onset of the warning signal for the next trial.

Each stimulus set was run on a separate day (the order counterbalanced over subjects). The remaining variables, SD, ISI, the eye, and the actual stimulus presented, were randomized within each day. Each day was divided into two sessions.

On all days, subjects were seated at the stereoscope and the mirrors were adjusted until the subject could see: an 8 with his right eye while his left eye was closed; an 8 with his left eye while his right eye was closed; and one 8 in the center of the scope when both eyes were open. Good binocular fusion was assumed if the subject passed the above test. The subject was then read instructions. In all cases, the subjects were told they were to respond verbally

to stimuli presented just after the warning tone. Subjects were to respond as quickly and accurately as possible. There were also informed that on some trials they would see one of several stimuli, but on the rest they would see only the mask.

Each subject was given a practice session of 10 trials with the stimuli and mask to be used in that session. The lights to the experimental chamber were off during the practice and experimental sessions. All subjects were given a 10-minute break between sessions. After their last sessions, the subjects were debriefed.

Results and Discussion

Reaction time, information transmitted, and information transmission rate for all the 24 experimental conditions, separately and pooled across some variables, are presented in Tables 1, 2, 3, and in Figures 3, 4, 5, 6, and 7.

Our main independent variable of interest is task. It had a highly significant effect ($p < 0.0001$) on all three dependent variables, reaction time, information transmitted, and information transmission rate.

For all three sets of stimuli and all four stimulus durations, reaction time was shortest for Detection, medium for Classification, and longest for Identification. This indicates that for the sets of stimuli tested, Classification does not take longer than Identification; reaction time is proportional to the amount of information to be processed in each task. Reaction time by itself, however, does not disclose in which task information is processed the fastest; only when reaction time is compared with the amount of information actually processed can this question be answered.

As could be expected, information transmitted generally increased from Detection to Classification to Identification, although the differences in information transmitted between Detection and Classification were small and

Table 1

Reaction Time (in msec)

Task/Stimulus Set	Signal Duration (in msec)				
	10	20	30	40	Average
Detection					
Symbols	1084	1124	1091	1105	1101
Single	992	1032	1025	984	1008
Missing	1083	1089	1143	1126	1110
Average	1053	1081	1086	1072	1073
Classification					
Symbols	1448	1440	1395	1413	1424
Single	1538	1365	1291	1315	1377
Missing	1330	1239	1226	1257	1263
Average	1438	1347	1304	1328	1355
Identification					
Symbols	2122	2214	2065	1667	2017
Single	1866	1561	1286	1325	1510
Missing	1635	1593	1486	1278	1498
Average	1875	1789	1612	1423	1675

Table 2

Information Transmitted per S-R (in bits)

Task/Stimulus Set	Signal Duration (in msec)					I(S)*
	10	20	30	40	Average	
Detection						
Symbols	.17	.18	.26	.27	.22	.81
Single	.23	.22	.26	.44	.29	.92
Missing	.05	.20	.21	.11	.14	.92
Average	.15	.20	.24	.27	.22	
Classification						
Symbols	.29	.25	.25	.18	.24	1.43
Single	.40	.33	.63	.52	.47	1.60
Missing	.40	.57	.76	.72	.61	1.60
Average	.36	.39	.54	.47	.44	
Identification						
Symbols	1.32	1.33	1.40	1.81	1.46	2.75
Single	.92	1.13	1.37	1.43	1.21	2.25
Missing	.95	1.21	1.35	1.63	1.29	2.25
Average	1.06	1.22	1.38	1.62	1.32	

*I(S) - amount of information conveyed per signal, and thus the upper limit for IT.

Table 3

Information Transmission Rate (in bits/sec)

Task/Stimulus Set	Signal Duration (in msec)				
	10	20	30	40	Average
Detection					
Symbols	.21	.17	.29	.30	.24
Single	.26	.25	.27	.49	.32
Missing	.04	.21	.20	.11	.14
Average	.17	.21	.25	.30	.23
Classification					
Symbols	.20	.16	.18	.11	.16
Single	.25	.26	.48	.40	.35
Missing	.29	.46	.61	.58	.48
Average	.25	.29	.42	.36	.33
Identification					
Symbols	.63	.61	.75	1.11	.78
Single	.55	.86	1.23	1.19	.96
Missing	.61	.79	.91	1.39	.93
Average	.60	.75	.96	1.23	.89

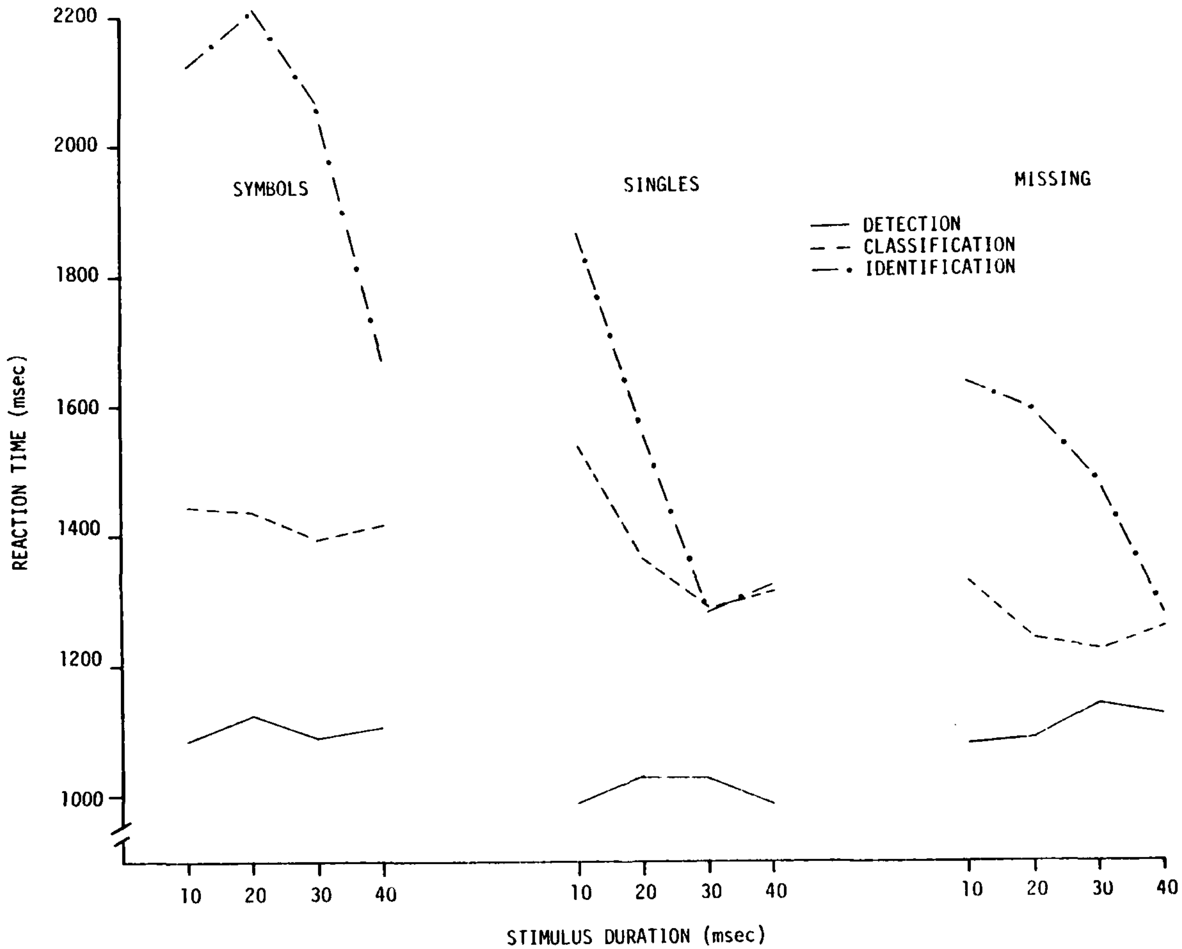

Figure 3. Reaction time as a function of the task, stimulus set, and stimulus duration.

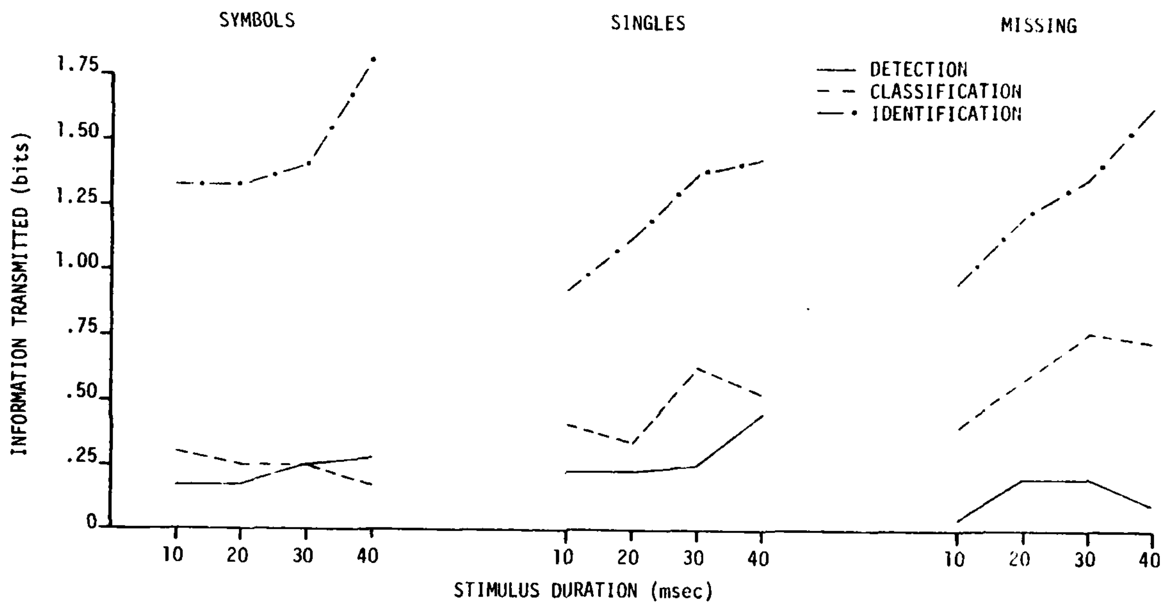

Figure 4. Information transmitted as a function of the task, stimulus set, and stimulus duration.

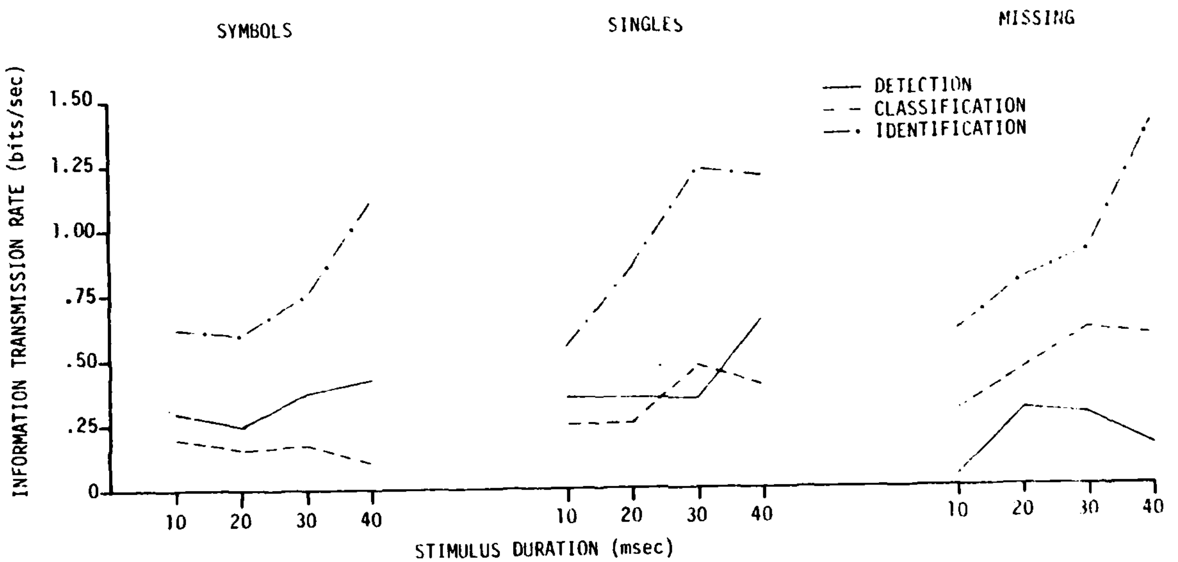

Figure 5. Information transmission rate as a function of the task, stimulus set, and stimulus duration.

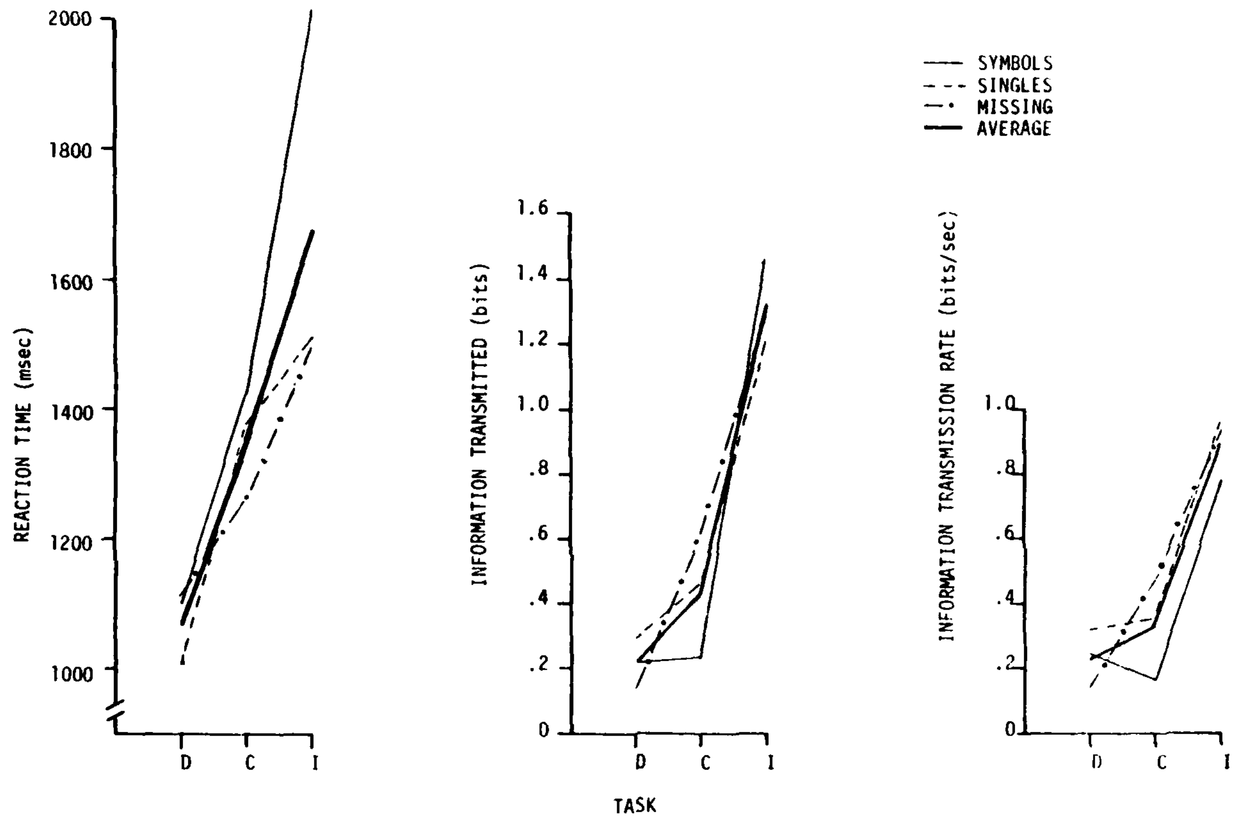

Figure 6. Reaction time, information transmitted, and information transmission rate as a function of the task (Detection, Classification, Identification) and the stimulus set, pooled for all stimulus durations.

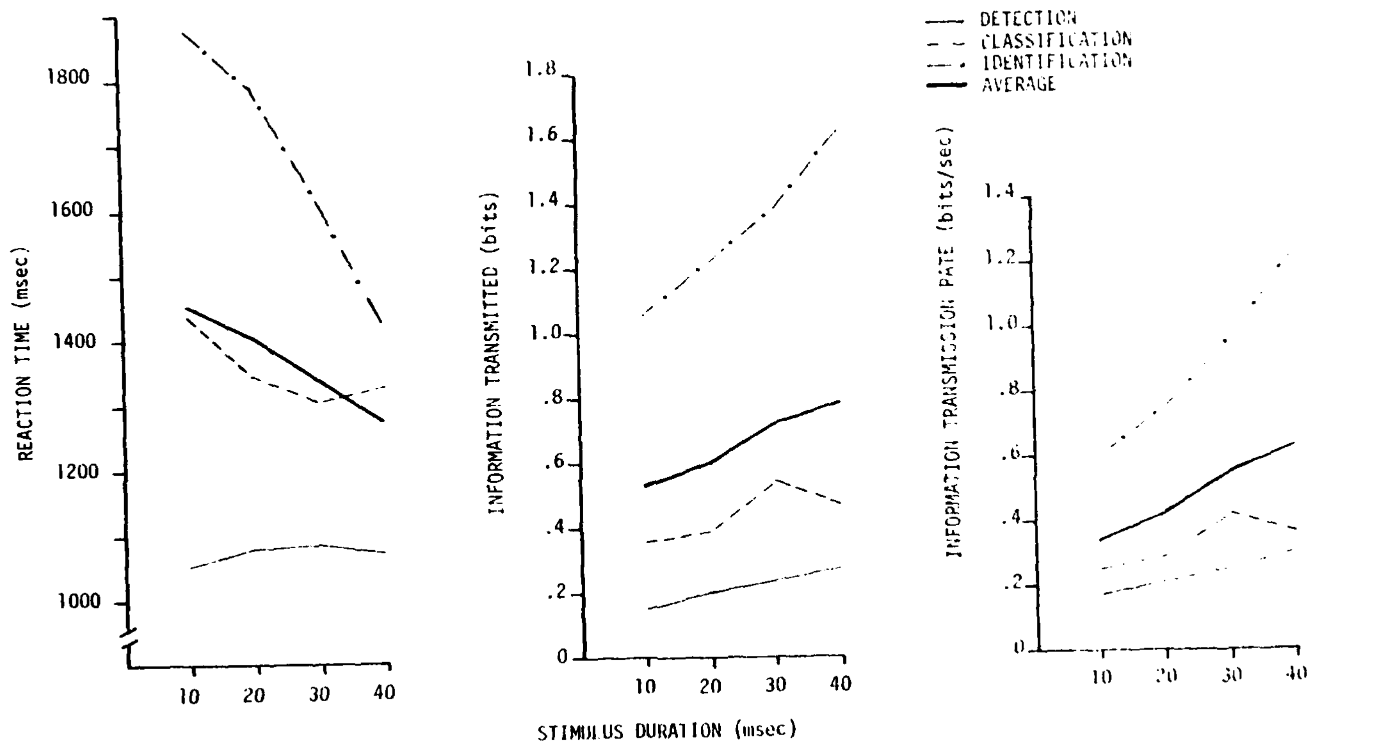

Figure 7. Reaction time, information transmitted, and information transmission rate as a function of the task and stimulus durations (pooled for all stimulus sets).

occasionally even reversed. Also, generally information transmitted was very low, especially in Detection and Classification when compared to the stimulus information. Information transmission rate revealed a picture exactly opposite to reaction time: information transmission rate was fastest for Identification, medium for Classification and, slowest for Detection.

As discussed before, Classification has been found to be either simpler or more complex than Identification, depending upon the sets of stimuli used and the degree of S-R compatibility. This is why the three sets of stimuli were tested. Indeed, stimulus set does have an effect on reaction time ($p < 0.02$): reaction time to Symbols was greater than that for Singles and Missing, especially for Identification. But there was no significant effect of stimulus set on information transmitted nor on information transmission rate ($p < 0.05$). Also, there were highly significant ($p < 0.0001$) task x stimulus set effects on information transmitted. Effects of this interaction on reaction time and information transmission rate were insignificant ($p > 0.05$), but they did reveal the expected trend: the reaction time for the identification of stimuli was longer than that for classification by 1.4, 1.2, or 1.1 times, respectively, for the Symbol, Missing and, Single task stimuli. This shows that while Classification is faster than Identification for all the three stimulus sets, the difference is much smaller for Singles and Missing (where S-R compatibility may be considered lower and the Classification rule less practiced) than for Symbols.

As expected, stimulus duration had a highly significant effect ($p < 0.0001$) on information transmitted and the information transmission rate: the longer the stimulus duration (within the tested range of very short stimulus durations), the greater the information transmitted, and consequently information transmission rate. Effects of stimulus duration on reaction time were much smaller and

did not reach significance level ($p > 0.2$). This latter finding is understandable when one compares the order of magnitude of reaction times (1 sec) with the order of magnitude of stimulus durations (10 msec): even if the subject deliberately waited for all the sensory information to come in before processing it, the eventual increase in time, from 10 to 40 msec, for the two most extreme stimulus durations would hardly show in his reaction time given the order of magnitude and variability of reaction times.

Also as expected, there was a significant ($p < 0.03$) effect of the task x stimulus duration interaction on information transmitted: The longer the stimulus duration the greater the difference in information transmitted between Identification and the other two tasks.

The main issue concerning testing the RC model for stimulus encoding is if the differences in reaction time to the three tasks--Detection, Classification, and Identification--can be accounted for by differences in RC without the necessity of assuming separate information processing stages for these three processes.

To examine this hypothesis the procedure proposed by Grice (1968, 1971, 1972a), based on Thurstone's (1925, 1927a, 1927b, 1928) scaling method was followed.

First the total range of reaction times for each of the three tasks was divided into arbitrary equal intervals. The interval of 100 msec was chosen as a unit for reasons of being both a round number and of dividing the whole range of reaction times into a reasonable number of intervals. Next, the frequency and the probability of a response, p(R), for each interval was computed. These p(R) values were subsequently converted into a cumulative probability distribution of responses over the time from stimulus onset, $p(R)_{cum}$. Finally, assuming that $p(R)_{cum}$ is normally distributed, the $p(R)_{cum}$ values were converted

to $\underline{z}$ scores (normal deviates). These $\underline{z}$ scores were plotted as a function of time from stimulus onset. If the assumption about normality of the $p(R)_{cum}$ distribution held, the data points (in $\underline{z}$ scores) should closely approximate a straight line. Indeed, for all the three tasks the data points approximated the straight line so closely that a formal test of the goodness of fit was neglected.

After thus establishing normality of $p(R)_{cum}$ distribution for all three tasks, the overlapping (over time) portions of $\underline{z}$ distributions for each task were plotted as functions of one another (for the three possible pairs: Detection vs. Classification, Detection vs. Identification, and Classification vs. Identification). For example, in plotting Classification data against Detection data, both coordinates would be scaled in $\underline{z}$ units. The abscissa would be designated as the Detection coordinate with the ordinate designated as the Classification coordinate. The $\underline{z}$ scores for Detection and Classification for the same time intervals would then be plotted accordingly. For instance, if $p(R)_{cum}$ = .5 ($\underline{z}$ = 0) for Detection for the time interval of 901-1000 msec, while for Classification for the same time interval $p(R)_{cum}$ = .2 ($\underline{z}$ = -.84), a point would be plotted on these coordinates: 0 for Detection and -.84 for Classification, and so on for all the time intervals for which $p(R)_{cum}$ distributions for the two tasks overlap. Thus, z_C distribution as a function of z_D was found. Such functions were dubbed by Grice (1971) REC--Response Evocation Characteristics curves.

REC has three characteristics important for further analysis: its shape (linear or not), its slope (parallel to the main diagonal, i.e., 45° or not), and its intercept (zero or not).

The most important for our purpose here is the first feature. If REC is linear, it means that the difference between the two experimental conditions

being compared can be accounted for by the two parameters of the RC distribution--its mean and its standard deviation. The linearity of REC provides evidence supporting the assumption that the variability of reaction times in both conditions being compared can be accounted for by a normally distributed RC in each condition, although not necessarily with the same parameters of the distribution. Whenever there are two normally distributed random variables defined over some dimension, in this case over time from the stimulus onset, their _z_ transformations are linearly related to each other. If the REC is not a straight line, some of the assumptions of the RC model do not hold and differences in the data cannot be fully accounted for in terms of differences in the RC paramter alone (Grice, 1971, 1972a, 1972b). In such cases, an additional separate stage of information processing would have to be hypothesized for the three tasks beyond the _a_-component stage. All three RECs were linear which indicates that the differences in task may be accounted for by differences in RC distribution parameters, i.e., that Detection, Classification, and Identification differ in RC parameters.

The theory postulates that the lower the RC the more quickly a stimulus can surpass this critical level and proceed to higher-level processes, thus leading to faster overall performance. Thus, obtained differences in RC could be used to account for differences in the response times associated with these tasks without the necessity of postulating differences in higher-level processing stages.

It should be noted that the linearity of REC implies only that the difference between the two conditions being compared can be explained by the differences in the RC distribution parameters, but it does not positively prove that they must be explained in this way. Other explanations are still possible, e.g., in terms of differences in the S-S translation between the two conditions

or in terms of an additional processing stage involved in one condition (e.g., Classification) and absent in another condition (e.g., Detection).

The second feature, the slope of the REC, reflects the ratio of the $\underline{z}$ units on each coordinate, and consequently the ratio of standard deviations of the two distributions plotted against each other. The slope of 45° indicates the ratio of one, or the equality of the two standard deviations. Only under these conditions is it meaningful to compare the means of the two distributions; otherwise, the means would be different in $\underline{z}$ units and the comparison would be misleading. For noe of the three RECs plotted was the slope equal to one: for D = f(D) it was 1.2; for I = f(D) it was 0.75; and for I = f(C) it was 0.6. To be able to compare the means of the distributions, the $\underline{z}$ units of one distribution have to be multiplied by the ratio of the two standard deviations to ensure that both distributions were scaled in the same units. That has been done, and hence rescaled RECs are presented in Figure 8.

When an REC is a straight line parallel to the main diagonal, its third feature, the intercept or the displacement from the main diagonal, provides a measure of the difference in mean RC. Figure 8 shows that if RC mean for Detection is accepted as an arbitrary zero (a reference point), then the RC for Classification is on the average, 0.67 z_D units higher, and the RC for Identification, 1.07 z_D units higher than RC for Detection. Thus, not only has it been shown that the differences between information processing in Detection, Classification, and Identification can be accounted for by the difference in mean RC levels, but also these differences in RC levels have been quantitatively estimated, and they show that the RC level is lowest for Detection, medium for Classification, and highest for Identification.

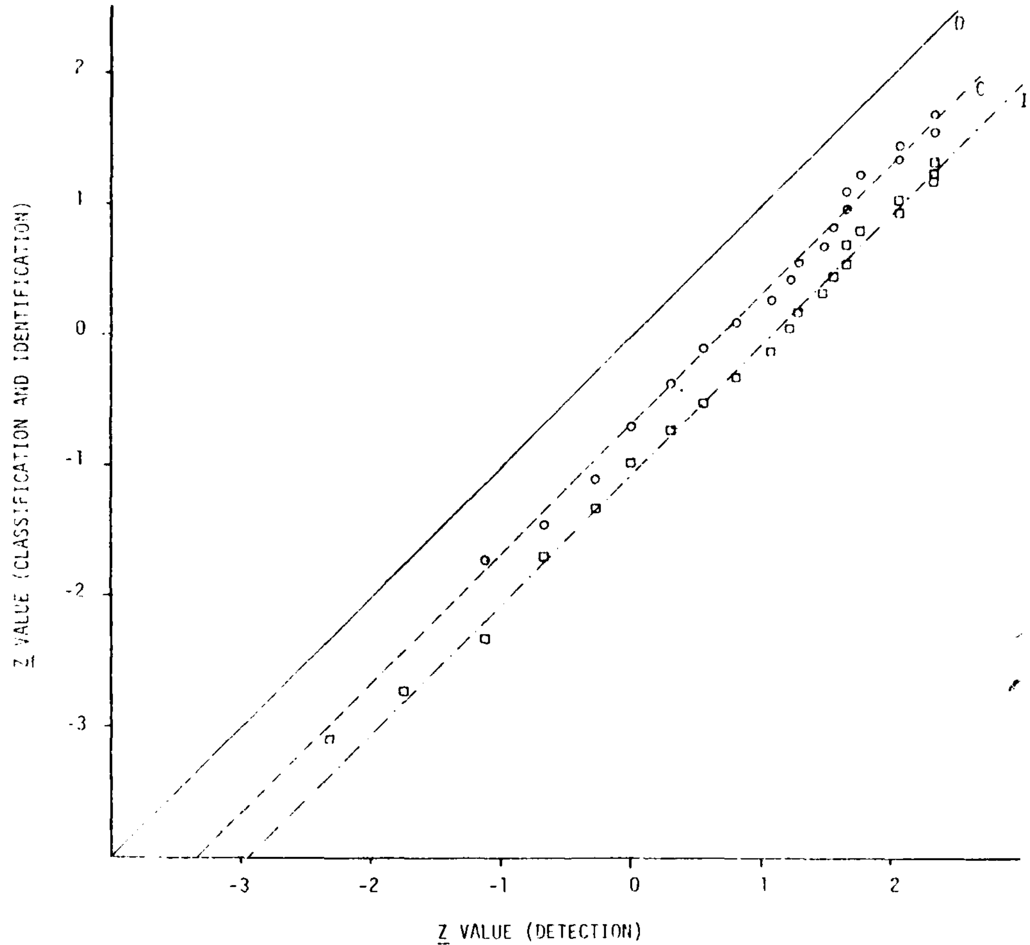

Figure 8. Response Evocation Characteristics curves relating normal deviates (z scores) for the response probability distributions over time from the stimulus onset, for Classification (C) and Identification (I) to that for Detection (D).

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Notes

1. Warren Teichner, the Principal Investigator for this project, has been developing his Information Processing Theory of Human Performance for several years before his death prevented him from completing the task. The experiments analyzed in this part of the report were designed by him to test some elements of his Theory, particularly what he called the a-component of human performance. He supervised carrying these experiments out. It was not given to him to analyze the data and to take another look at his Theory in view of the results of these experiments. Since I have been collaborating with Warren for several years and information processing/human performance has been my field for many years, I took up to finish this last task he left behind. Although, having closely watched and participated in the development of Warren Teichner's Theory, I am familiar with the Theory as well as with the experiments, it has to be born in mind that only the author of both could be in the best position to bring the two together. Therefore, it is almost certain that I will be missing some important points which Warren would have tried to make. The reader should be aware of the peculiar feature of this part of the report: it is one man's effort to carry out another man's intentions.
2. The name "a-component" has been adopted by Teichner to relate his Theory to the early theorizing by Donders (1869). Donders' idea was to measure the time consumed by mental processes by making people perform tasks of varying complexity and then subtracting the reaction time to the simpler task from the reaction time to the more complex task; the difference--Donders reasoned--was the amount of time consumed by the mental process involved in the more complex task but absent from the simpler task.

Specifically, Donders studied three types of reaction time tasks which he denoted by letters: (a) simple reaction time, in which the subject was to respond always with the same simple movement to the same stimulus, and which--according to Donders-- was consumed by neural transmission, (b) choice reaction time, where several stimuli were presented and the subject was to respond in a different way to each stimulus, which was supposed to require stimulus categorization and response selection, and (c) selective reaction time, where several stimuli were presented but the subject was to respond only to one of them always in the same way, which Donders interpreted as requiring stimulus categorization but no response selection. Subtracting RT_c from RT_g Donders hoped to measure the response selection time and RT_a from RT_c the stimulus categorization time. The whole process of sensory information processing is nowadays considered much more complicated but to honor Donders' tradition Teichner calls the initial stage of this process, corresponding roughly to Donders', a-component, using the same name.

3. The ISI variation was later found ineffective so the data were pooled together for both ISI levels and this variable is not even considered in the data analysis.

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COMPRESSION OF STIMULUS INFORMATION IN AN INFORMATION-SEEKING TASK

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As man-machine systems become more advanced, the role of man in these systems is increasingly becoming that of a remote information seeker and monitor-type display systems are coming into common usage. A great deal of research is being dedicated to the design of display systems to be of use in information transmission to the human operator. Among the variables which must be accounted for in the design of information displays are those related to the ability of the human operator to encode, process, and respond to symbolic and pictorially displayed information. The encoding, processing, and response to information has been conceptualized by Teichner and his associates (Teichner, 1974; Teichner & Krebs, 1974; Teichner & Williams, 1979) by the following formula:

$$P = f_1(a) + f_2(S\text{-}S) + f_3(S\text{-}R) + f_4(R\text{-}Sel) + f_5(R\text{-}Ex) \tag{1}$$

where performance, _P_, is expressed as a measure of speed or accuracy or a combination of speed and accuracy such as information transmission rate. This measure of performance is contributed to by that portion of the response measure associated with stimulus acquisition, _a_; the portion due to translations between stimulus codes, _S-S_; the portion due to the selection of a motor program necessary to execute the action, _R-Sel_; and finally, _R-Ex_, the portion of the response related to the performance of the motor activity. _R-Ex_ is generally considered to be a constant for well practiced activity.

Performance may be affected by changes in the functional or message complexity of the task. The functional complexity of a task refers to the number of stages of processing or subtask functions and processes which are required

by the operator in performing these tasks. Code complexity, on the other hand, is based on the relationship between the stimulus input code and the response output code or the number of possible messages in the response set. Stimulus, response, or display variables which act to affect the functional or message complexity of a task will in turn affect overall performance. Information coding systems or display variables which create the necessity for additional subtasks or processes, e.g., S-S or S-R translations, thereby increasing functional complexity would increase processing time and the opportunity for error. Performance would be enhanced by variables which produce reductions in functional complexity. Variables affecting message complexity may or may not affect functional complexity but would affect the ability of the human operator to perform various subtasks and may therefore increase or decrease overall performance.

Stimulus, response, or display variables which affect the ability of the human operator to perform one or more of the subtasks or processes by affecting message complexity or which change the number of subtasks involved, functional complexity, would be expected to affect performance in the task as a whole. Variables such as the structure of the display (e.g., Mocharnuk, 1978; Reilly & Teichner, 1962; Shaw, 1969), the stimulus dimensions chosen to display information in symbolic form (e.g., Garner, 1974, 1976; Lockhead & King, 1977; Monahan & Lockhead, 1977), the size of the display (e.g., Holmgren, 1975; Mocharnuk, 1978; Teichner & Krebs, 1974) and display duration (e.g., Mocharnuk, 1978) have all been found to affect information processing presumably by affecting the _a_-component in Teichner's model (1979). Other variables may be assumed to affect performance by affecting the post-acquisition stages, for example the redundancy of information contained in the individual stimulus elements (e.g., Fitts, Peterson & Wolpe, 1963; Garner & Lee, 1962), the com-

patibility of stimulus and response codes (e.g., Bindra, Donderi & Nishisato, 1968; Morton, 1969; Stanovich & Pachella, 1977) and the size of the stimulus and response sets from which the information has been drawn (e.g., Crossman, 1953; Hyman, 1953).

Display, stimulus, and response variables are not independent of one another and they may interact to influence performance at either the same or different subtask levels. One display variable which has been found to interact with stimulus information variables is that of the compression of stimulus information. Compression has been found to enhance performance under conditions in which there is a high amount of redundancy among symbols within messages (Williams, Moffitt & Teichner, 1978). Compression involves the reduction of stimulus information within units rather than the reduction of units of information. Like an identification task, the S-S translation for a task involving compressed information consists of a one-to-one translation rather than a many-to-few translation, as in a classification task. A common example of compression is the abbreviation of language such as "msec" for milliseconds.

Compression of stimulus information has been postulated (Williams et al., 1978) to affect performance by decreasing the amount of processing time associated with the a-component. The recoded information should require less external processing in the form of eye movements thereby enabling faster stimulus acquisition. Furthermore, since the recoded stimulus messages contains less information than the uncompressed source stimuli, increased effectiveness of information processing should result from a decrease in translation time and/or errors in making translations beyond the initial S-S translation.

The compression of stimuli should, according to the Teichner model (Teichner & Williams, 1979, see Section A), result in an S-S translation

related to the compression of the information, in addition to those translations normally required for response to uncompressed information. In hypothesizing the effects of this additional S-S translation on information transmission rate, it may again be assumed that the smaller the amount of information in the recoded message (the greater the compression), the faster should be the translation, the less the error involved in making the translation and the more rapidly it should be learned. Therefore, the additional S-S translation would be less disruptive to performance the greater the level of compression. However, even maximal compression has to involve more time than no recoding of stimulus information at all. The usefulness of compressing information is a function of the trade-off between the loss in speed due to the addition of an S-S translation and the gain in speed and accuracy in subsequent S-S and S-R translations and in the a-component.

The effects of compression on performance may also be a function of task variables such as the type of response which is required to the compressed information. If the task response can be based on the stimuli in their compressed form, a greater amount of facilitation would be expected than if the information must be restored to its uncompressed state for response. The restoration of the compressed information requires a few-to-many translation (creation task) on the part of the operator. Like the S-S translation associated with compression, the additional S-S translation due to creation would be predicted to proceed faster and with less error the greater the level of compression, as less information would be involved in making the translation.

In the present study we proposed to examine the effects of different levels of stimulus compression upon information processing of visually displayed information. Compression occurred at one of two phases in an information seeking task. In one phase, the operator's response was independent of

the level of compression; in the other phase the operator was required to restore the compressed information in order to make a response. The data over trial blocks was examined to determine the effects of practice on compression. The cost effectiveness of the compression was also examined.

Method

Subjects

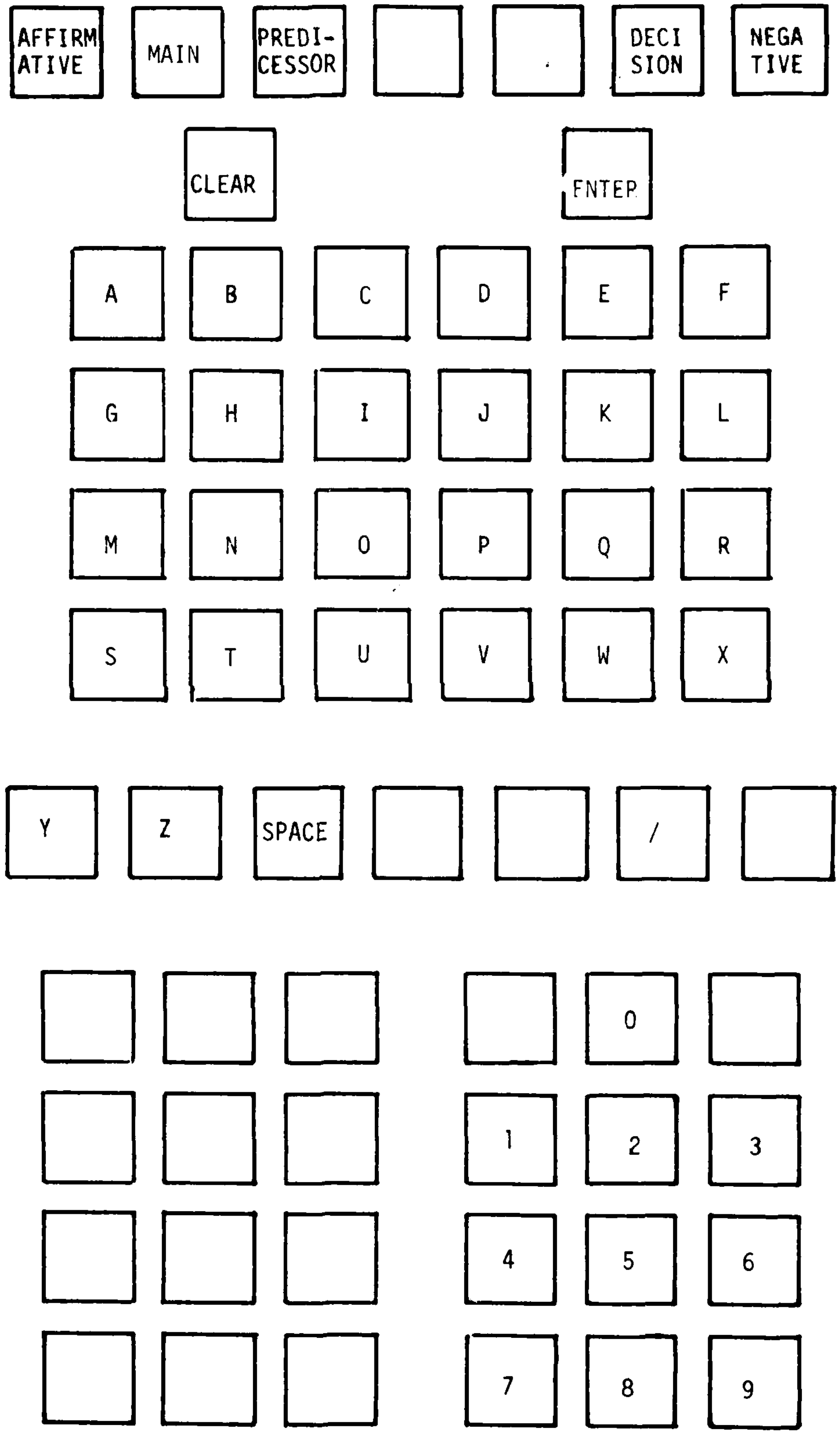
Eight university students served as subjects in this experiment. Each was required to have English as his or her primary language, have eyesight corrected to 20/20 vision, and have had no previous experience as a civilian or military aviator. Subjects were paid $2 per experimental session.

Apparatus and Stimuli

Stimuli were presented to the subject on a 165 x 210 mm CRT display screen. Task information, printed in white against a bright green background, was displayed in close proximity to the center of the screen below a depicted midscreen horizontal line. A readout providing notification of either a correct or incorrect response was presented directly above the midline after each trial response was made. Capital letters and numerals used in stimulus presentation were each 1 x 2 mm. Eye-to-display distance was approximately 535 mm.

The panel used by the subjects for response to the stimuli consisted of 78 push buttons and one circular "finger rest" point mounted on a 255 x 380 mm board tilted 10° toward the subject. Response key layout and labeling of the response panel are presented in Figure 1. Each key had a 12 x 12 mm impact surface which extended 16 mm above the board's surface. Button depression distance was 4 mm. Adjacent rows of buttons were 25 mm apart, measured from centerline to centerline. Major separation of button sections had a centerline gap of 36 mm. The "finger rest" circle, being flush with the

Figure 1. Response key arrangement and labeling of response panel.



response board surface, was centered 36 mm below the centerline of the row of buttons. All buttons were unlabeled, each having a dot depicted in the center of its impact surface.

During the experiment, subjects were required to wear earphones through which white noise, produced by a remote generator, was being introduced. To prevent subjects from responding before the stimulus information was presented on the screen, a time delay circuit was incorporated to electrically delay response time sensing for 20 msec following the completion of stimulus display. A program tape, fed through a PDP8/e computer located in a room adjacent to the experimental room, was used to present stimuli on the display screen. A teletype machine, also located in the adjacent room, operated in conjuntion with the computer program and keyboard apparatus to provide a printout of all response times.

Experimental stimuli were derived from the Aviation Preflight Outline presented in Table 1. This information network was headed by a selection of information areas consisting of seven major aviation preflight categories. Selection of a numeric response key associated with any of these categories would lead to the presentation of a logically related list of items at a level of information one step lower. In two cases, this constituted the lowest information level; i.e., the level at which the subject's decision was to be made. In the other cases, selection of an item listed at this second level of information would lead to the presentation of a list of related lower level information items.

All tasks involved the subject's pursuit of realistic responses (e.g., "500 FEET") to realistically desired preflight planning information (e.g., "MINIMUM REQUIRED CEILING; DESTINATION QAB"). Five basic task sequences consisting of eight practice trials and 42 experimental trials were used. These

Table 1

Preflight Outline: Diagram of Information Network

PREFLIGHT

1 MISSION
2 NAVIGATION
3 WEATHER
4 AIRFIELD
5 REFUEL
6 TARGETS
7 AIRCRAFT

MISSION

1 COMBAT AIR PATROL

COMBAT AIR PATROL

1 TIME ON STATION
2 ALTITUDE
3 FUEL REQUIRED
4 ORDINANCE REQUIRED
(Missiles, Rounds, Bombs)
5 VISIBILITY REQUIRED
6 PATROL DURATION

NAVIGATION

1 DEPARTURE TO COMBAT AIR PATROL
2 COMBAT AIR PATROL TO DESTINATION
3 COMBAT AIR PATROL TO REFUEL
4 REFUEL TO DESTINATION

Any of the above

1 HEADING
2 ALTITUDE
3 GROUNDSPEED
4 DISTANCE
5 TIME ENROUTE

WEATHER

1 DEPARTURE
2 COMBAT AIR PATROL
3 REFUEL
4 DESTINATION

DEPARTURE or DESTINATION

1 CEILING
2 VISIBILITY
3 SURFACE WINDS
(Direction, Velocity)

COMBAT AIR PATROL or REFUEL

1 CLOUD TOPS
2 VISIBILITY ON TOP

Table 1 Continued

PREFLIGHT

1 MISSION
2 NAVIGATION
3 WEATHER
4 AIRFIELD
5 REFUEL
6 TARGETS
7 AIRCRAFT

AIRFIELD

1 DEPARTURE
2 DESTINATION

Any of above

1 RUNWAYS
(Numbers, Lengths)
2 MINIMUM REQUIRED CEILING
3 MINIMUM REQUIRED VISIBILITY

REFUEL

1 RENDEZVOUS TIME
2 ALTITUDE
3 VISIBILITY REQUIRED
4 PLANNED OFFLOAD
5 DEPARTURE TIME

TARGETS

1 AIR
2 GROUND

AIR

1 TYPE
2 NUMBER
3 DISTANCE
4 HEADING
5 ALTITUDE
6 GROUNDSPEED

GROUND

1 TYPE
2 NUMBER
3 DISTANCE

AIRCRAFT

1 CEILING
2 MAXIMUM SPEED:NORMAL
3 MAXIMUM SPEED:COMBAT
4 FUEL CAPACITY
5 FUEL CONSUMPTION RATE:NORMAL
6 FUEL CONSUMPTION RATE:COMBAT
7 ORDINANCE CAPACITY
(Missiles, Rounds, Bombs)
8 MINIMUM TAKEOFF DISTANCE
9 MINIMUM LANDING DISTANCE

basic sequences were derived by making a random sequence selection of 35 preflight tasks which were, themselves, randomly selected from the 65 possible Preflight Outline Information parthways. The trials in each sequence consisted of tasks which differed in the number of response alternatives at the decision point (from one to six alternatives). Each basic sequence was organized to contain an equal number of tasks within each response alternative condition; the order of presentation of conditions within each sequence was determined randomly.

The stimuli as described were used in an uncompressed form for the display training and the task pretraining sessions. In the experiment proper, the stimulus sequences were identical with those used in the pretraining sessions with the exception that certain phrases used in the stimulus information presented on the subject's video monitor were presented in abbreviated or compressed form. Three categories of compression were used: high compression in which stimuli were abbreviated to very short forms, low compression in which the stimuli were abbreviated to a lesser extent, and a control condition in which the stimulus information was left in its unabbreviated form. The degree of compression for specific tasks within each category was necessarily limited by the qualities of individual task terminology. The level of compression for all messages was determined by an application of information theory (Shannon & Weaver, 1962) suggested by Teichner and his associates (Teichner & Williams, 1979; Williams, Moffitt & Teichner, 1978). Thus the formula used for determining the coefficient of compression was:

$$\mu_c = L_c/L_s \tag{2}$$

with $\underline{L_s}$ being the average length of the original message or source code:

$$L_s = \Sigma p_{s_1} (S_1) \tag{3}$$

and $\underline{L_c}$ referring to the average length of the recoded messages. It should be

noted that according to these formulas, the more a message is compressed from its original form, the smaller μ_c. For purposes of determining the amount of information in the messages and the coefficient of compression, each letter and space in a given message was counted as a unit of information. Based on these formulas, the average coefficient of compression for the high-compression condition was .33 with a range from .12 to .53 for individual messages within tasks. For the low-compression condition, the average coefficient of compression was .65 with a range from .47 to .86 for individual messages. In all cases, there was a graduated amount of compression or abbreviation of individual messages when going from the high to the low control conditions. For example, given the control message, "TIME ON STATION: COMBAT AIR PATROL," the high-compression form of the message was "TM ON STAT: CAP," with a .22 coefficient of compression and the low-compression form of the message was "TM ON STAT: COM AIR PAT," with a coefficient of compression of .67.

On any compressed information trial, only the initial task question and the final decision information were presented in compressed form; all other intermediate step information remained in its uncompressed form. Distribution of the compressed task statements at the different levels of compression was done randomly throughout the five basic task sequences with the constraint that there was an equal distribution of high, low, and control statements within each of the response alternative conditions (either 1, 2, 3, 4, 5, or 6 response alternatives) when combined over all of the five stimulus sequences, with relatively equal distribution within each sequence. On any given task-trial, only one level of compression was used.

Procedure

Prior to participation in the task pretraining sessions or in the experiment proper, each subject was given a session in keyboard training and two sessions in display training followed by 10 task pretraining sessions.

These sessions were presented on separate days. The keyboard training session consisted of 200 preprogrammed trials in which the subjects became familiar with the response button locations. During the first 100 keyboard training trials, subjects had a labeled diagram of the response keyboard to aid them in their responses. For the second 100 trials, subjects were to make their keyboard location identification responses from memory. For subjects to proceed in the experiment, it was required that they miss less than 10% of this second set of location identifications. In the event that a subject missed more than 10% of the identifications, he was eliminated from the experiment. One subject was eliminated on this basis and a new subject took his place so as to provide a total of eight experimental subjects.

During each of the two sessions following the keyboard training, subjects received 73 Display Training trials in which they became acquainted with the experimental tasks. For the first Display Training session, subjects used a diagram of the preflight information network (see Table 1) to aid them in their responses; in the second session this diagram was removed and subjects responded to task information questions from memory.

In the task pretraining sessions which followed, subjects were presented with the experimental task sequences. Subjects received one task sequence daily for 10 consecutive working days. Each of the five basic experimental task sequences was presented to the subject twice with the order of administration of these sequences being determined randomly for each subject. Eight preliminary practice trials were presented to the subjects each day prior to the presentation of the 42 experimental trials. The practice trials were used to eliminate warm-up effects due to the time separation between experimental sessions.

Instructions stressed the requirement that the dominant index finger be used in making all trial responses and that it be returned to the "finger rest" circle following each response entry (with the exception of the final decision entry).

In the task pretraining, as in the experiment proper, subjects were instructed to perform the task according to the following procedures:

1. In response to the information seeking question presented on the display, subjects were to press the response key which signified the number associated with the next level of information required for the task. Upon pressing this response key, the subject finalized his response by pressing the "ENTER" key and returning his finger to the rest position.

2. Upon presentation of the second level of information, the subject chose a response which would result in the next level of relevant information being displayed. This step was repeated until the final information level was displayed or until the subject pressed the decision key.

3. At the final information level the subject was presented with the information requested in the original task question. This information was embedded among varying numbers of distractor items. In this phase, subjects were to press the "DECISION" key followed by typing out the response information requested in the original task question.

Sample Task

(For an outline of the information network, refer to Table 1.)

```
(screen)        DETERMINE MINIMUM REQUIRED CEILING:DESTINATION QAB
                                1.  MISSION
                                2.  NAVIGATION
                                3.  WEATHER
                                4.  AIRFIELD
                                5.  REFUEL
                                6.  TARGETS
                                7.  AIRCRAFT
```

(subject's task) Identify the task and enter the number corresponding to the category to which the task is related. In this example, the correct category is "AIRFIELD."

Action: Press response key "4", press "ENTER" and then return finger to finger rest.

(screen) DETERMINE MINIMUM REQUIRED CEILING:DESTINATION QAB
<u>AIRFIELD</u>: 1. DEPARTURE
2. DESTINATION

(subject's task) Identify the appropriate information area and enter the corresponding number on the keyboard. The correct area for the example is "DESTINATION."

Action: Press response key "2", press "ENTER" and then return finger to finger rest.

(screen) DETERMINE MINIMUM REQUIRED CEILING:DESTINATION QAB
ANY OF ABOVE: 1. RUNWAYS, LENGTHS (NUMBERS, LENGTHS)
2. MINIMUM REQUIRED CEILING
3. MINIMUM REQUIRED VISIBILITY

(subject's task) Identify the appropriate information area and enter the corresponding number.

Action: Press response key "2", press "ENTER" and then return finger to finger rest.

(screen) DETERMINE MINIMUM REQUIRED CEILING:DESTINATION QAB
DESTINATION TFX: 800 FEET
DESTINATION QAB: 500 FEET
DESTINATION BUB: 200 FEET

(subject's task) Identify the minimum required ceiling for the Destination QAB and enter it as the decision.

Action: Press "DECISION"; press "ENTER"; press the response keys including space key which spells out "500 FEET"; press "ENTER"; then return finger to finger rest.

If the subject performed the task correctly, the computer advanced to a new task question. If any of the task responses were in error, an error message appeared followed by the return of task presentation to the starting point. If subjects recognized an error in their response sequence in a given task, they were to correct their errors by using the "CLEAR" key and two other keys which returned them to earlier levels in the information network ("MAIN" and "PREDECESSOR").

Subjects were required to perform the tasks in the experiment proper in the same manner as in the task pretraining trials. All decisions and responses had to be typed out by the subjects in their non-abbreviated form regardless of whether the task information was being displayed in a compressed or uncompressed form. Instructions stressed the need for both speed and accuracy. Particular emphasis in instructions was placed on the necessity for proper use of the "finger rest" between responses and on the desirability of immediate entry of the response to the information seeking question if the correct response was recalled prior to its visual presentation at the end of the information network. Due to the repetitive nature of the training and experimental task, the skipping of information levels to make a response to the task question was possible. Early response to the task question was accomplished by pressing the "DECISION" key and typing out the data required by the task question.

In the experiment proper, subjects received the 10 experimental sequences previously presented in the task pretraining sessions. Information in these sequences was presented in compressed form. Task sequences were presented one-per-day for 10 consecutive working days. In the first block of five sessions, subjects received each of the five different stimulus sequences once these sequences were repeated in the second block of five trails. The order of presentation of the sequences was random within each session block. Each experimental session included eight warm-up trials followed by 42 experimental task trials.

Results and Discussion

Time measures on task pretraining and experimental sessions were obtained for each subtask response and for the total task time combined over subtasks. Measures of accuracy were also obtained for each task. Response time measures

for four phases of task performance were analyzed: (a) response time to the initial task question, (b) time from the final information presentation to the pressing of the "DECISION" key, (c) time to type out the information required by the task question, and (d) total task time. The only time data which was analyzed was that from error-free trials. The data were also analyzed to determine the number of trials in which subjects skipped information levels to respond to the initial task question. The results of this analysis over the 10 experimental sessions indicated that subjects skipped information levels a total of 16 trials. These information skips were randomly distributed over the eight subjects and the experimental conditions throughout the 10 experimental sessions.

The time data from the 10 task pretraining sessions were analyzed to determine if there was any difference in response time as a function of the number of distractor items in the final information presentation and to determine if the subject's performance had begun to stabilize over practice. Average response times for the four phases of the pretraining task are presented in Table 2 as a function of pretraining session. Response time decreased over practice for all phases of the task. Performance had apparently not stabilized as response time was still decreasing up to the tenth pretraining session. Analyses of variance over the four time measures indicated a significant practice effect on response time to the Task Question, $\underline{F}$ (9, 63) = 20.43, $\underline{p} < .01$; Decision, $\underline{F}$ (9, 63) = 10.46, $\underline{p} < .01$; Response Output Time, $\underline{F}$ (9, 63) = 15.80, $\underline{p} < .01$; and Total Task Time, $\underline{F}$ (9, 63) = 53.23, $\underline{p} < .01$. The analysis of the pretraining sessions indicated that the only phase of the task which was affected by the number of distractors was the time to type out the response to the task question, $\underline{F}$ (5, 35) = 4.17, $\underline{p} < .01$. While statistically significant, this time difference does not show a consistant increase

Table 2

Mean and Standard Deviations (σ) of the Response Time (in msec) to the Initial Task Question, Time from the Presentation of the Final Task Information to the Pressing of the Decision Key, Time to Output (Type) the Response to the Task Question and, Total Task Time as a Function of the Pretraining Session.

Pretraining Session	Task Question		Decision		Output Response		Total Task Time	
	Mean	σ	Mean	σ	Mean	σ	Mean	σ
1	4925.35	1220.64	3302.60	2126.99	11347.52	3935.24	25685.98	6634.28
2	3889.44	1237.56	2233.96	953.88	10158.25	2642.37	21012.29	3529.34
3	3275.75	872.47	2028.67	1110.10	9183.12	2880.64	18869.15	4138.00
4	3305.19	1119.77	1832.42	727.06	8736.85	2905.02	18757.94	4485.57
5	2982.58	964.27	1659.35	858.36	8496.81	2706.08	17339.21	3642.79
6	3032.48	909.08	1736.81	799.53	7640.79	2411.49	16014.54	3343.90
7	2661.33	640.69	1435.17	674.88	7765.19	2546.23	15354.73	2885.13
8	2726.81	862.06	1433.94	619.91	7896.38	2701.46	15222.33	3088.94
9	2730.42	796.76	1358.50	739.23	7456.98	2303.48	15009.88	3261.21
10	2484.92	816.31	1268.31	655.82	7544.23	1772.66	14837.19	2670.15

with an increase in the number of distractor items as there was a reversal at three and five distractors. Furthermore, the effect of distractor items was found to be unrelated to the level of practice.

The average time to make the first categorization response to the task question, time from the presentation of the final information presentation to the "DECISION" key, time to type out the response to the task question, and total task time along with their associated standard deviations are presented in Table 3, for error-free trials as a function of experimental session and level of compression. As can be seen, when the data are averaged over all sessions, the response time to the uncompressed information trials is faster at all phases in the information seeking task than that to the compressed information trials. Furthermore, the greater the amount of compression the slower the responses. This difference in response time was only significant for the task question, $F\ (2, 14) = 26.19$, $p < .01$, and total task time, $F\ (2, 14) = 17.42$, $p < .01$. Response times to the decision key and response output showed a similar trend but failed to reach statistical significance, $p < .05$. There was no significant effect of the number of response alternatives nor significant interaction of this variable with any other variable. The difference in response time between the different compression conditions may be accounted for in terms of an added S-S translation which the operator would have to perform on the compressed information and which was not required for the uncompressed information. In that the increase in response time increased as a function of the level of compression, it could be hypothesized that the time required for this S-S translation was at least initially a function of the similarity of the compressed message to the original message. This finding appears to be contrary to our earlier predictions in which it was suggested that the speed of the S-S translation would be a function of

Table 3

Mean and Standard Deviation (σ) of the Response Time (in msec) on Error-Free Trials to the Initial Task Question, Time Between the Presentation of the Final Task Information and the Pressing of the Decision Key, Time to Type Out the Answer to the Task Question and Total Task Time

Compression Level	Session	Task Question		Decision		Output Response		Total Task Time	
		Mean	σ	Mean	σ	Mean	σ	Mean	σ
High	1	3536.37	1291.09	1207.98	744.13	7791.52	2502.81	17056.60	5457.03
	10	2112.56	612.91	987.71	763.20	6581.64	3079.00	13589.79	8162.02
	All	2630.71	681.50	1081.49	654.43	6866.65	2121.48	13943.62	3110.44
Low	1	3124.94	1768.48	1202.91	853.16	6892.08	2960.97	15391.83	7163.89
	10	2257.81	1083.31	919.77	557.63	6339.64	2559.23	12432.94	4038.08
	All	2433.26	734.46	1042.03	643.23	6603.99	1462.29	13297.32	2928.38
Control	1	2659.75	1573.33	1104.45	633.09	7090.31	3024.00	13801.93	4711.53
	10	2175.25	713.35	947.14	633.28	6855.75	2885.49	12831.21	4986.36
	All	2231.20	638.34	1018.51	573.26	6552.73	1559.35	12645.78	2687.34

the amount of stimulus information in the recoded or compressed message. It was hypothesized that the greater the compression, the less the absolute amount of information in the message, and therefore, the faster the S-S translation should be accomplished.

It is possible that the finding of greater interference in performance the greater the level of compression may be due to negative transfer of training. The subjects in this experiment were well practiced in the information seeking task using uncompressed messages. Due to the high level of learning, changes in the task produced interference with the level of interference being related to the level of change. Once this negative transfer effect is overcome, it is possible that the speed at which the S-S translation is performed will be an inverse function of the amount of information in the compressed message. To examine this possibility, the data were examined as a function of the level of practice with the compressed messages.

The data from the first experimental or compression session are in accord with the combined data, indicating the fastest response times for the control condition with the high-compression condition showing the slowest response times and the low-compression condition intermediate. As the subjects became more familiar with the compressed form of information this trend in results was changed. Trials in which there was a high level of information compression tended to benefit the most from practice over sessions. Response times on the high-compression trials in the first as compared to the tenth experimental session were reduced approximately 1424 msec in the initial categorization response to the task question, 200 msec from the presentation of the last level of information and the pressing "DECISION" key and 1209 msec in the outputting of the response. These difference scores over levels of practice can be compared with the time differences for the initial task question,

decision, and response output for the low-compression trials: 867, 283, and 552 msec respectively, and 484, 157, and 235 msec respectively for the control trials. This decrease in response time as a function of practice was significant for total time and response time to the initial question, $F(1, 7) = 12.87$, $p < .05$, and $F(1, 7) = 9.25$, $p < .05$, respectively. The only time measure to show a significant interaction between practice and the level of compression was the time to the initial task question, $F(2, 14) = 5.97$, $p < .05$. These differences in response time cannot be explained by a speed-accuracy trade-off as the errors for all three compression levels did not differ significantly from one another nor were they significantly affected by practice, see Table 4.

The response times to the compressed information not only showed greater difference scores as a function of practice but performance on the tenth experimental session indicated that one or both of the compressed information conditions was superior to the control condition on all phases of the task. The high-compression condition showed the fastest response time to the initial task question, while the fastest response times to the decision for response output and the total task were produced in the low-compression condition. Which of the two compression conditions was found to experience the greatest amount of facilitation may have been a function of the information translations required by the compression of the information at different phases in the task. Response to the initial task question in a compressed form would require an additional S-S translation over that required by the uncompressed information in the control condition. Response to the "DECISION" key and to output the answer to the task question required not only an additional S-S translation in encoding the information presented on the screen, but also required later many-to-few S-S translations involving the creation of information. These

Table 4

Mean Percentage of Error Trials for Each Level of Compression Over the Ten Experimental Sessions

Level of Compression	Experimental Sessions										
	1	2	3	4	5	6	7	8	9	10	Average
High	10.71	18.75	17.86	12.50	13.39	11.61	11.61	12.50	16.96	15.78	14.16
Low	12.50	13.39	11.61	12.50	9.82	12.50	8.04	11.61	11.61	15.18	11.87
Control	10.71	14.29	11.61	6.25	10.71	16.07	15.18	16.07	14.29	18.75	13.39
Average	11.31	15.48	13.69	10.42	11.31	13.39	11.61	13.39	14.29	16.57	

S-S translations were associated with the need to restore the compressed information to its original uncompressed form in order to make a response. The differences in response time between the two compressed conditions and the control condition were not significant for the decision, response output, or total task. While compression obviously facilitates performance on the initial task question, the lack of any significant amount of facilitation for the later stages in the task is probably due to the time required for the additional S-S translation involving creation.

Under conditions in which no creation of information is required for response, the ordering of response time as a function of the level of compression are as would be predicted by the Teichner and Williams (1979) model. As evidenced by the greater facilitation of the high- than the low-compression conditions over practice, the rate of learning the S-S translation associated with compression was an inverse function of the amount of compression. Furthermore, given sufficient practice, the amount of time required to make the S-S translation would be inversely related to the level of compression. Thus the enhanced performance of the high-compression condition can be accounted for by facilitation occurring in the a-component and later S-S and S-R translations which would more than compensate for extra steps in information processing. In the low-compression condition, the rate of learning of the S-S translation should be slow. Also, due to the higher information content in the messages relative to high compression, the making of the S-S translations would be slower and facilitation in the a-component and later translations would be less. The limited facilitation in processing would be unable to compensate for the additional S-S translation and slowing down of the response rate would be expected. This is what was found in the low compression condition. This implies that with further practice processing of messages

at low levels of compression would become faster than uncompressed messages. Partial support for this prediction comes from the finding that the decrease in response time with practice was greater for the low-compression condition than the control.

While the amount of time required for later S-S and S-R translations cannot be directly measured to provide further substantiation of the above explanation of the data, Grice and his associates (Grice, 1968, 1971, 1972a, 1972b, 1977; Grice, Nullmeyer & Spiker, 1976) have devised a scaling technique which will enable a comparison of a portion of the a-component. The a-component of Teichner's model consists of that part of response time associated with the preliminary sensory processing of information. The a-component, as proposed by Teichner, involves a variable response criterion (RC). According to the model, a stimulus must reach a certain criterion level in the build-up of neural impulses, the RC, before the stimulus information will be processed beyond a sensory storage level. The RC for any particular stimulus is a function of stimulus probability, instructions, familiarization, motivation, etc. Given the hypothesis that the compression of information should enhance processing in the a-component, it is reasonable to assume that this compression should affect the response criterion.

According to Grice's scaling technique, RC differences are reflected in differences in receiver-operator characteristics (RECs) associated with the distribution of different experimental conditions. To establish these RECs, response times to the initial task question for the three compression conditions were arranged in cumulative probability distributions, $p(R)_{cum}$, using 500-msec intervals. Extreme $p(R)_{cum}$ scores falling in the lower and upper .005-percentiles of the distributions were eliminated to increase reliability and decrease variability. The $p(R)_{cum}$ values were then converted to normal

deviates (*z* scores). The conversion of *z* scores assumes that the time data are normally distributed. To evaluate this assumption, the *z* scores were plotted as a function of time from stimulus onset. This plot should result in a straight line if the distribution is normal. The plots for all three compression groups closely approximated straight lines.

To establish the REC curves, the *z* scores of the high- and low-compression conditions were converted into standard deviation units of the control group and were plotted as a function of the control groups' *z* scores. Only those *z* scores which overlapped in terms of the time interval from stimulus onset were used. For a further explanation of the establishment of RECs for comparing the RC of different distributions of data, see Grice (1971).

Once the RECs have been established and plotted in equivalent standard deviation units, Grice's model (1968, 1971, 1972a, 1972b, 1977) suggests that differences in the RECs represent differences in the RC. The REC curves for the high- and low-compression conditions in this experiment are presented in Figure 2. These RECs are plotted in comparison and in standard deviation units of the control condition. As indicated, the RC for the control condition is the highest, followed by the RC for the low-compression condition, with the RC for the high-compression group being the lowest. The difference in RC between the control and the low-compression conditions was .15 units with .25 units between the high- and low-compression conditions.

The obtained differences in the RECs and therefore in the RCs for the different conditions imply that the compressing of the stimulus information lowers the RC, enabling the stimulus information to enter the system more quickly. These data suggest that stimulus compression does lessen the amount of time required for the processing of information in the *a*-component.

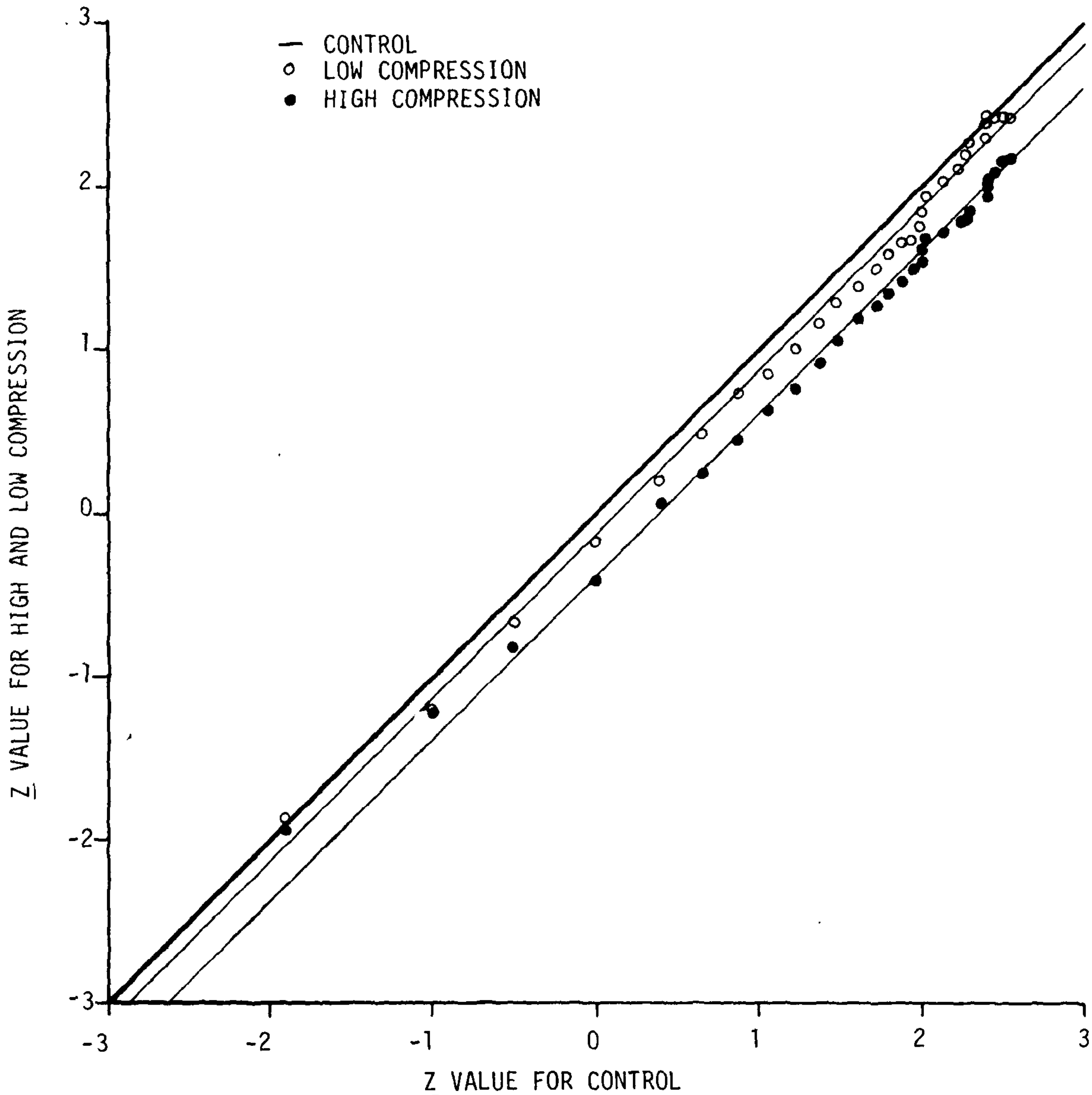


Figure 2. RECs for the control, low-, and high-compression groups transformed into standard deviation units of, and plotted in comparison to, the control group.

The goal in designing information displays for communication to the human operator is to utilize those display variables which will enhance performance and reduce complexity in the information processing task without negating this facilitation by interference at another level. Since compression has been found to facilitate performance at one level while increasing the number of translations and consequently processing time at another level, it is important to determine the relative cost or gains associated with this type of information recoding; i.e., a measure of the cost effectiveness of recoding is required. An initial attempt toward the development of such a cost effectiveness measure has been suggested by Teichner and his associates (Teichner & Williams, 1979, see Section A; Williams, Moffitt & Teichner, 1978). In a visual information task, cost is measured in terms of the time required to acquire, process and respond to the stimulus information. Therefore, any change in the coding of stimulus information must be measured relative to its accompanying change in time and accuracy. Accordingly, Teichner and Williams have proposed that:

$$R = b(1 - \mu_c) \tag{4}$$

where $\underline{\mu_c}$ is the unit of recoding based on the ratio of the recoded message to the original message, $\underline{R}$ is the rate of information processing, and $\underline{b}$ is the slope of the function relating $\underline{R}$ to stimulus recoding. Therefore:

$$CE_c = b = \frac{R}{(1 - \mu_c)} \tag{5}$$

where $\underline{CE_c}$ is the cost effectiveness of compression. Thus, the slope relating $\underline{R}$ to compression is the measure of the cost effectiveness of recoding. These formulas may be restated in terms of reaction time (RT) such that:

$$RT = k(1 - \mu_c) \tag{6}$$

and

$$CE_c = -k = \frac{-RT}{(1 - \mu_c)} \tag{7}$$

where $\underline{k}$ is the slope of the function relating RT to compression and $\underline{CE_c}$ is equal to the inverse of the slope relating RT to compression. The cost effectiveness ratio reflects the fact that cost effectiveness would be expected to increase with decreases in reaction time.

Given the finding of significant differences in RT to the initial task question as a function of both compression and practice, the cost effectiveness of compression was examined at different practice levels. A plot of the slopes relating RT to compression over the 10 different practice sessions is presented in Figure 3. The slopes were based on the least-squares fit of RT and the level of compression $\underline{(1 - \mu_c)}$. A constant of 1 was added to all compression scores to eliminate the zeroes associated with the compression level of the control group as zeroes cannot be used in determining the least-square fit. The addition of this constant would serve to affect the intercept of the least-squares fit but would leave the slopes unchanged.

As shown in Figure 2, the slope relating RT to compression is very high for initial levels of practice. As the cost effectiveness of compression is the inverse of the slope, this suggests that the cost effectiveness of compression is low, -1308.71, during the first few trials in which compression is introduced. Over practice, however, the slope relating RT and compression decreases and becomes negative and the cost effectiveness of compression increases to 103.57. These data reflect the fact that compression of information tends to interfere with performance when it is first introduced, but this relationship tends to change over trials until compression begins to enhance performance. The exact relationship between cost effectiveness, compression and practice cannot be determined based upon the data obtained in this experiment as performance and cost effectiveness of recoding is still improving with practice. With continued practice it would be anticipated

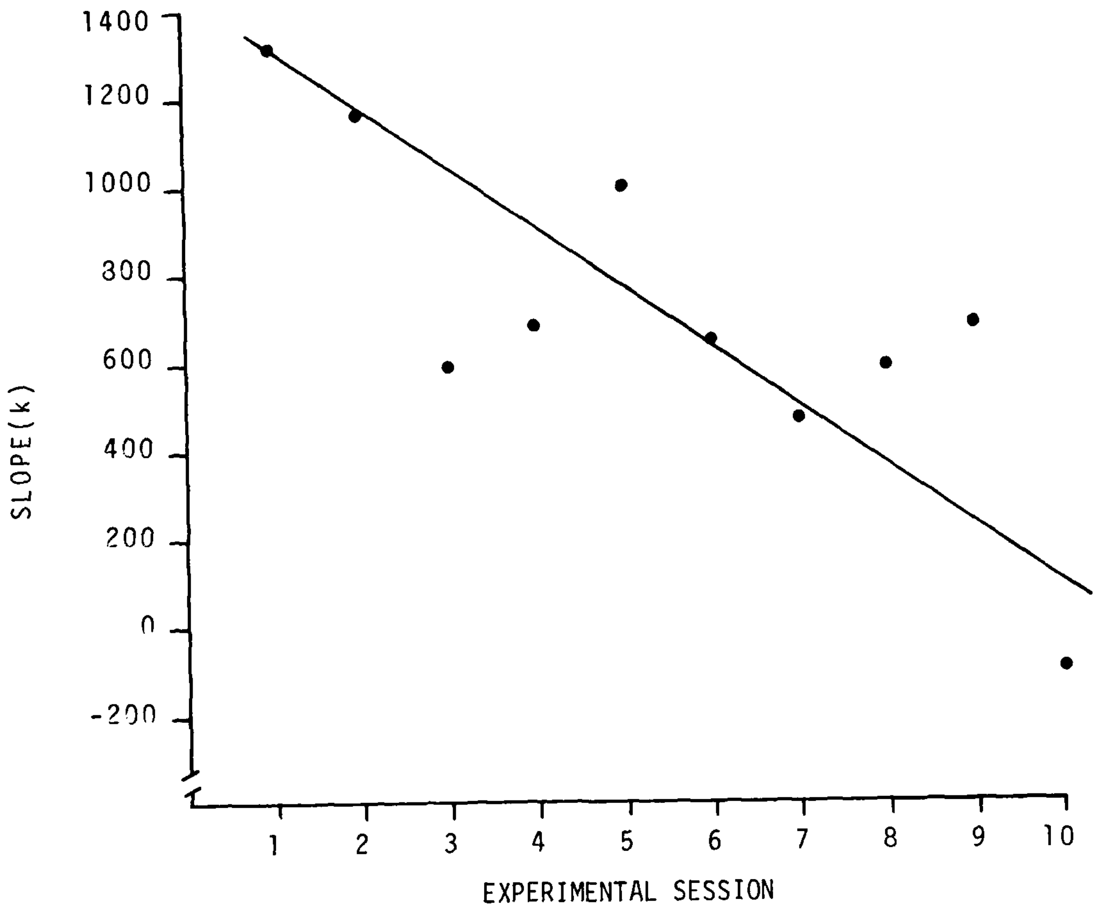


Figure 3. Slope constants (k) from Equation 7 as a function of the number of experimental sessions.

that cost effectiveness would reach assymptote and would no longer improve with practice. Over the level of practice given in the present experiment, however, the function relating cost effectiveness, or *-k*, to practice can be determined by obtaining the least-squares fit of the slopes over the practice sessions. The function obtained for the inverse of the slopes (*-k*) plotted in Figure 2 is:

$$CE_{cp} = 103.07\ Np - 1269.30 \tag{8}$$

with CE_{cp} referring to changes in the cost effectiveness of compression over practice, *Np* to the number of practice sessions in which there were 14 trials a piece of each level of compression. Acknowledging its limitations, this formula could be interpreted to determine how much practice would be necessary to make compression generally cost effective. Further research needs to be conducted to provide a more accurate function relating the cost effectiveness of compression to extensive practice with compressed information displays.

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INFORMATION PROCESSING OF DIFFERENT STIMULUS-RESPONSE LEVELS IN IDENTIFICATION AND CLASSIFICATION TASKS

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According to the Teichner model (Teichner, 1974; Teichner & Krebs, 1974; Teichner & Williams, 1979, see Section A), information processing tasks can be defined in terms of the subtask functions and processes which are required by the operator in performing these tasks. The complexity of a task can be partially defined in terms of the number of stages of processing involved; this is known as functional complexity. Code complexity represents a second type of complexity which involves the relationship between the input code and the output code. Code complexity is based on the number of possible messages in the stimulus set as related to the number of possible actions or messages in the response set. The processing rate within the system varies as a function of both functional and code complexity. Given a single-channel system, functional complexity would be inversely related to processing time and accuracy. Tasks which require fewer subtasks or processes would be accomplished more quickly and with fewer opportunities for error. The relationship of code complexity to information processing rate is dependent upon the number of stimuli relative to responses, on whether any symbol reduction or creation of information is necessary, or if some of the stimulus information must be filtered prior to making a response.

A beginning step toward answering the question of the relationship of information processing time relative to code complexity can be taken by a comparison of the information translations and associated temporal aspects of identification and classification tasks. Identification is a task in which the operator is required to make a unique response to each stimulus presented, thus

there is a one-to-one translation between the stimulus and response. Classification, on the other hand, is a task which requires the operator to place stimuli into categories. This type of task involves a reduction of messages such that there is a many-to-few translation between stimuli and responses (Teichner, 1974). By comparing identification and classification at different levels of stimulus-response information, the effects of the number of stimulus messages, response categories, and number of messages per category can be determined. Previous research indicates that information processing in identificaton and classification tasks is dependent upon the type of stimuli, S-R compatibility, and degree of learning as well as stimulus and response coding factors (Crossman, 1953; Morin, Forrin & Archer, 1961; Posner, 1964). In this paper we will attempt to concern ourselves mainly with informational factors relevant to the stimulus and response messages while holding other variables constant.

Much of the research involving the level of stimulus and response uncertainty has been directed toward temporal comparison of identification and classification tasks. Pierce and Karlin (1957) investigated the time required for the identification of stimuli relative to their classification into one of two categories while varying the size of the stimulus set. When only two stimuli were used the classification task was faster than identification, however, as the stimulus population increased the temporal relationship was reversed with the binary classification requiring 40% longer than identification. The identification task, however, involved a highly overlearned verbal naming response while the classification task was less practiced (key press to male-female or animal-vegetable categories). Furthermore, reaction time by itself does not indicate the rate at which information is being processed. This can be determined only as a function of response time in conjunction with the amount

of information processed through the system. The maximum information available to be transmitted by the classification task was one bit and this maximum did not vary as a function of size of the stimulus population. In the identification task the maximum information available for transmission increased monotonically with the size of the stimulus population.

Crossman (1953) used information measures to examine performance in a card-sorting task which varied the number of categories for classification while maintaining a constant number of stimuli. All of the conditions in this study involved many-to-few translations as all categories were fewer in number than the stimuli. Response times were, in general, found to be related to the amount of information transmitted. In those cases where the relationship did not hold, the authors postulated that the difference was due to perceptual difficulties with some of the categorizations.

Again using information measures, Bricker (1955) varied the number of categories into which stimuli had to be classified. Subjects were presented with eight light patterns which had to be classified into 8, 4, or 2 response categories. Bricker found that response uncertainty as measured by the number of potential response categories had no consistent effect upon the rate of learning, but was positively related to reaction time. He concluded that the relationship between response uncertainty and reaction time was independent of stimulus uncertainty. This conclusion was based upon the assumption that the amount of information necessary for making an accurate response should increase with response uncertainty, and the finding that learning proceeded at the same rate under all conditions of response uncertainty. In order to convincingly test Bricker's conclusion, however, it would be necessary to directly vary the amount of stimulus information as well as response information.

Using a word classification task, Pollack (1963) found that classification time was substantially more sensitive to the number of response categories than to the number of examples per category. The two variables were found to interact, however, with the functions relating number of examples to response time, increasing in slope with increases in the number of categories. Pollack's results also indicate that there may be a difference in the processes involved in a classification with a many-to-few translation, as compared to identification with a one-to-one translation. He found that when there were between 2 and 24 items per category, response time showed a linear relationship with the logarithm of the number of items. When extrapolated to include identification, the condition in which there was a one-to-one correspondence between stimuli and responses, the logarithmic function did not fit the obtained data. Response time in the identification condition was significantly less than would have been predicted from the logarithmic function.

Other researchers have related response time and information transmitted in a classification task with the amount of information reduction produced by using successively fewer response categories (e.g., Pollack, 1963; Posner, 1962). These studies have indicated that the difficulty of the task in terms of reaction time and errors was an increasing linear function of the amount of information reduced.

If there are temporal differences in the cognitive processes associated with classification and identification tasks, as suggested by Pollack's data, and differences in the rate of information processing for different levels of classification (e.g., Bricker, 1955; Crossman, 1953; Pierce & Karlin, 1957; Pollack, 1963; Posner, 1962), the next question to ask would be at what stage or stages in processing do these differences exist. Then the next step would be to establish functions to relate stimulus and response uncertainty to response time.

According to the Teichner model (Teichner, 1974; Teichner & Williams, 1979; see Section A), performance differences in tasks may exist at any of five subtask levels as represented by the formula:

$$P = f_1(a) + f_2(S\text{-}S) + f_3(S\text{-}R) + f_4(R\text{-}Sel) + f_5(R\text{-}Ex) \quad (1)$$

where a is that portion of response time associated with stimulus encoding. According to the model, the a-component provides decisions about sensory events which establish the probability of further stimulus processing. In order for a stimulus to be processed beyond a sensory storage level, the stimulus must reach the response criterion (RC) set for it. This RC represents the criterion number of neural pulses which must be accumulated before a stimulus will receive further processing. The level of the RC for any particular stimulus is established as a function of stimulus probability, instructions, familiarity, motivation, etc. The S-S function is that associated with a translation between a feature code and a name or verbal label code. The S-R function represents that portion of time which would be required for a translation between the final stimulus code and the response code; R-Sel is the portion due to the selection of a motor program for carrying out the action required by the response code; with R-Ex relating to the amount of time necessary for neural and motor actions associated with executing the response.

Ekel and Teichner (1979; see Section B) have used the Teichner model in analyzing the response times associated with detection, classification, and identification tasks using different types of stimulus items, either alphanumeric symbols, incomplete squares with one side missing, or single sides of a square. In the detection task subjects were asked to indicate whether or not a stimulus was present; in the classification task subjects made a binary categorization; while in the identification task the alphanumeric symbols were named and the side of the square which was single or missing was identified.

It was found that the three tasks showed differences in the amount of information transmitted with identification showing the highest amount followed by classification and then detection. The response times to these tasks were inversely related to the amount of information transmitted. An examination of curves of the response evocation characteristics (REC) using the method developed by Grice (Grice, 1968, 1971, 1972a, 1972b, 1977; Grice, Nullmeyer & Spiker, 1977) led the authors to conclude that these differences in information processing rate could be a function of differences in response criterion. For a further explanation of this method and its conceptualization, see Section B.

In this study, we will examine the rate of information processing and response criterions as represented by tasks involving one-to-one translations and various levels of many-to-few translations in an attempt to determine functional relationships between processing time and the number of stimuli, number of responses, and the amount of information reduction. Once these functional relationships have been established, they will be examined in light of the Teichner model.

Method

Subjects

The subjects were 30 introductory psychology students, 15 males and 15 females, who volunteered to participate in the experiment as partial fulfillment of a class assignment. The following restrictions were placed on the volunteers: (a) all subjects had to have 20-20 vision or vision corrected to this level, (b) the primary language of the subject had to be English, and (c) all subjects had to be right-handed.

Apparatus and Stimuli

The stimuli were slides of 24 eight-sided, outlined random shapes (see Figure 1). Each slide contained one random shape. These random shapes were

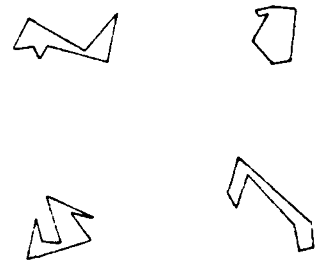

Figure 1a. Random shapes used in 4-stimuli tasks and their arrangement on the response panel for Matrix 1.

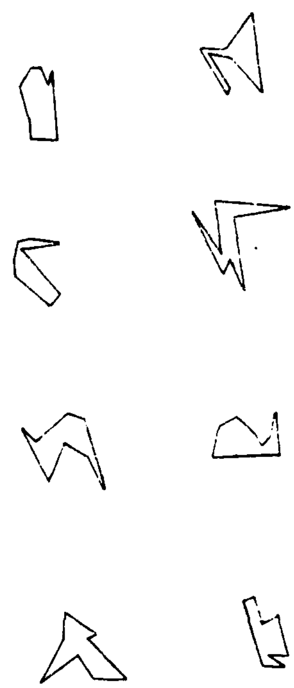

Figure 1b. Random shapes used in 8-stimuli tasks and their arrangement on the response panel for Matrix 1.

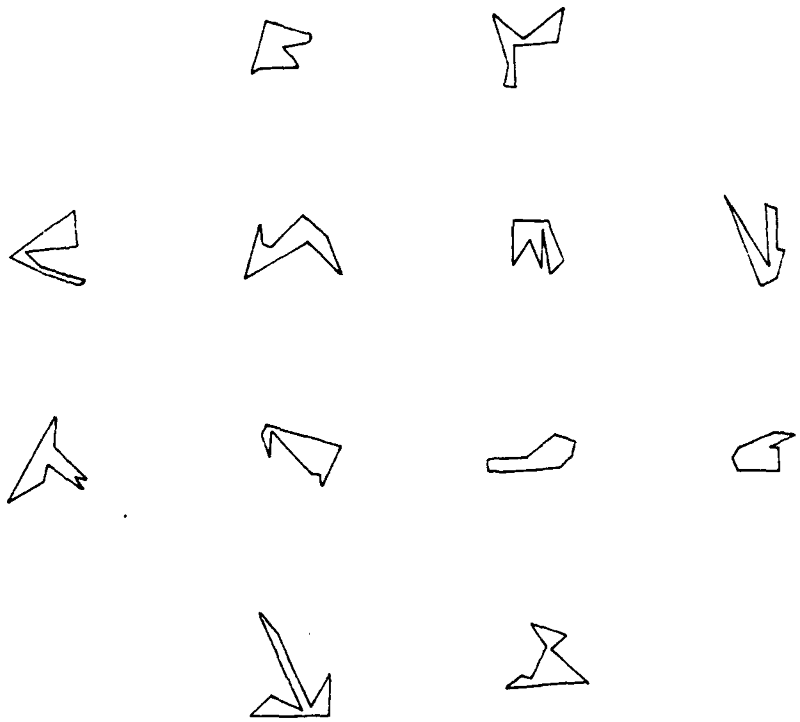

Figure 1c. Random shapes used in the 12-stimuli tasks and their arrangement on the response panel for Matrix 1.

randomly assigned to the groups of 4, 8, and 12 shapes, each used for the different experimental groups presented with different amounts of stimulus information. All stimuli within each condition were presented equally often. The slides were presented to the subjects by means of a Kodak Carousel 750 slide projector. Stimulus duration of 400 msec was controlled by a Uniblitz Electronic Shutter interfaced with a Digital PDP8/e computer.

The subjects' response panel was an in-house built wooden panel measuring 60.96 cm x 15.24 cm. The response panel contained 64 response metal buttons arranged in four matrices of 16 buttons each and one additional resting response button placed in the center of the panel. The four matrices of response buttons were located in the four quadrants of the response panel (see Figure 2). Responses were made by pressing the response buttons with a metal stylus. The response panel was interfaced with the computer so that the computer recorded the time from stimulus onset to response and the specific button pressed.

<u>Procedure</u>

Three male and three female subjects were assigned at random to one of five experimental groups. The groups differed in the number of stimulus items with which the subjects were presented and the number of possible responses in the second matrix used in the experiment. Subjects were presented with either 4, 8, or 12 stimulus items. When responding to Matrix 1 subjects made a different response to each stimulus, thus there was a one-to-one correspondence between the stimuli and response alternatives. The number of possible responses for Matrix 2 was reduced resulting in a many-to-few translation from the stimulus to the response alternatives. The six subjects who received 4 stimulus items were reduced to two response alternatives in Matrix 2. Two groups of six subjects each were presented with 8 stimulus items and two groups with 12 stimulus items.

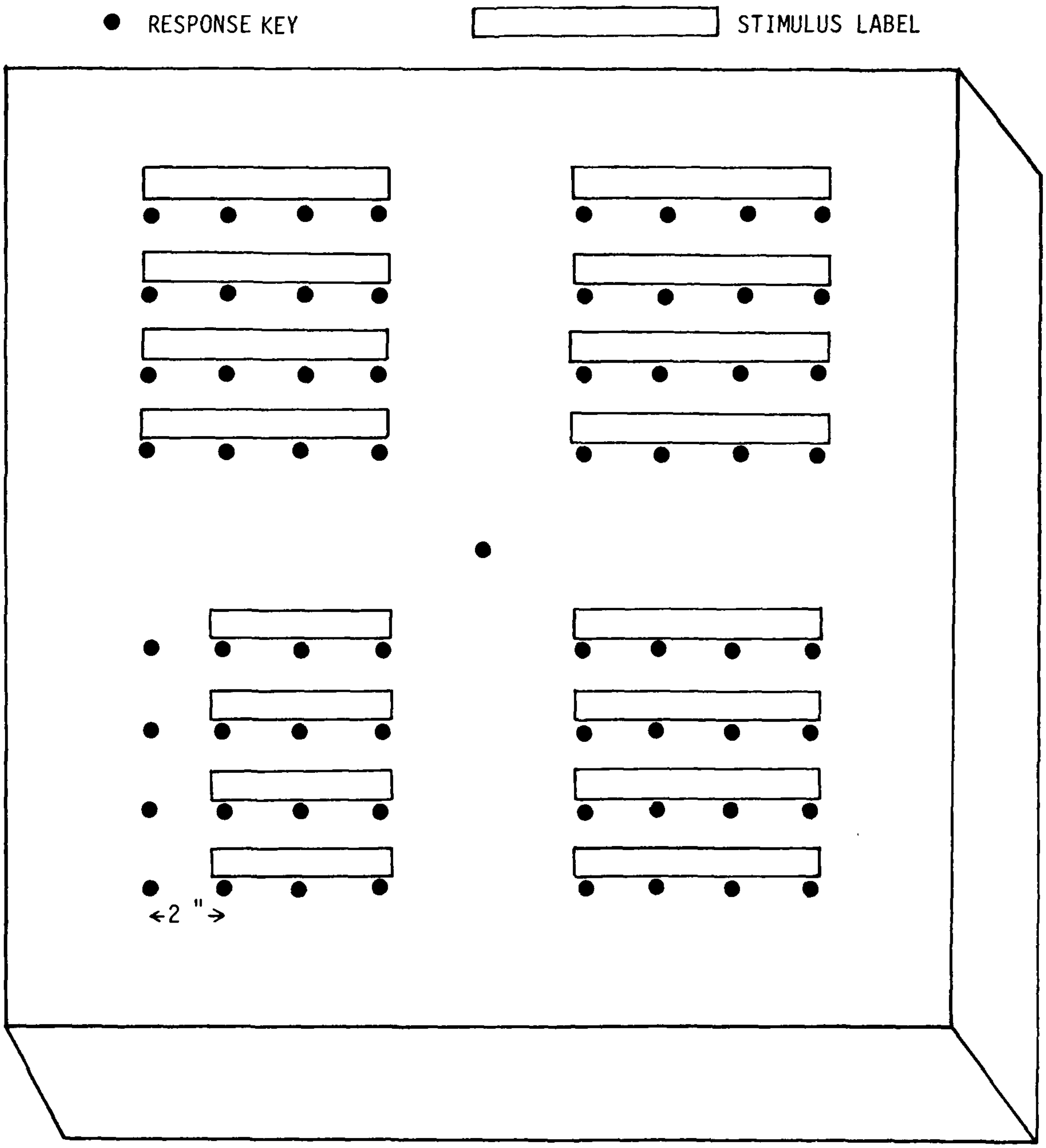

Figure 2. Subject response panel indicating arrangement of response keys and stimulus labels.

When responding to Matrix 2, one of the subject groups at each stimulus level had its response alternatives reduced to two while the other group of subjects had its response alternatives reduced to four.

The general procedure for all of the experimental groups was the same. All subjects were run individually and participated in the experiment in two separate phases. In Phase I subjects responded to Matrix 1, the matrix in the upper left-had corner of the subject's response panel. In this phase of the experiment, subjects received 320 trials. On each trial the subjects were presented with one of the stimulus items designated for their experimental condition. The subject responded to the stimulus by pressing a stylus to the metal response button which corresponded to the stimulus. The response panel was labeled with small replicas of the random shapes located above the associated response key. The stimuli used for the three levels of stimulus information and their location in relation to one another on the response panel are presented in Figure 1.

Phase II of the experiment immediately followed Phase I. Responses in Phase II were made to Matrix 2, in the upper right-hand corner of the response panel, and involved a many-to-few classification of the stimuli from Phase I. The stimuli from Phase I were randomly assigned to either two or four response locations depending upon the experimental condition. An equal number of stimuli were assigned to each response location within each experimental condition. The response panel was labeled so that replicas of all of the stimuli associated with a particular location were presented above that location. The middle four response buttons were used as the response locations for the four-response alternative groups. Response buttons located in columns 2 and 3 of row 3 were used for the two-response groups. Subjects received 320 trials in Phase II.

In both phases of the experiment the rate of presentation of the slides was self-controlled by the subject. When the subject was ready for a trial to begin, he or she initiated the trial by pressing the stylus to the metal response button located in the center of the response panel. Upon contact with the center response button, the slide projector advanced to the next stimulus and the stimulus was presented for 400 msec. Subjects were instructed to respond as quickly and accurately as possible. In the event of an incorrect response, subjects were to continue in the task without trying to correct their error.

Results and Discussion

Comparisons of processing differences in identification tasks (Matrix 1) and in classification tasks (Matrix 2) as well as across stimulus-response levels of classification and identification tasks can be made by examining the dependent variables of response time, information transmitted, and information transmission rate. The average reaction time, information transmitted and information transmission rate for the five classification groups are presented in Tables 1, 2, and 3 respectively. Response time in Table 1 is based solely on error-free trials. As can be seen, response time is greater for Matrix 1 where there is a one-to-one correspondence between stimuli and responses than in Matrix 2 where there is a many-to-few translation, F (1, 25) = 212.81, $p < .001$. This difference in response time between identification and classification tasks is dependent upon both the number of original stimuli and the number of categories into which the stimuli are to be classified in Matrix 2. The greater the number of items to be classified and the greater the number of categories into which they are to be classified, the longer the response time and the greater the difference between identification and classification. The effect of level of stimulus-response uncertainty (4:2, 8:2, 8:4, 12:2, 12:4) was significant, F (4, 25) = 9.407, $p < .001$, as was the

Table 1

Average Reaction Time (in msec) and Standard Deviation (σ) for Correct Responses in Matrix 1 and Matrix 2 as a Function of Stimulus:Response Information

Group	Matrix 1 (Identification)		Matrix 2 (Classification)	
	Mean	σ	Mean	σ
4:2	844.53	157.36	672.43	122.47
8:2	1180.77	299.95	845.65	147.93
8:4	1189.28	352.70	973.22	199.60
12:2	1647.56	585.44	844.53	157.71
12:4	1459.18	457.82	1195.38	255.23

interaction between level of stimulus-response information and matrix, $\underline{F}$ (4, 25) = 18.678, $\underline{p}$ < .001.

The only variable found to be related to information transmitted was the amount of potential or stimulus information. Information transmitted in the identification task, Matrix 1 of Table 2, increases as a function of stimulus information. The greater the amount of information potentially available for transmission, stimulus information, the greater the amount of information transmitted. This same relationship holds for Matrix 2. The fewer the categories into which the subject is classifying the information, the less information there is available for transmission and the less the amount of information transmitted. There was no consistent effect of the number of items per category upon information transmitted. Information transmitted decreased as a function of information reduction in the four-category conditions while decreasing and then increasing for two-category conditions.

Response time and information transmitted as analyzed above, indicates that both of these measures are higher for identification than for classifiation. Differences in one or the other of these measures could be taken to reflect processing differences in identification and classification. However, the dependent variables of information transmitted and response time can only reflect differences if they are examined in relation to one another. A system can process an infinite amount of information if there is an infinite amount of time available for processing the information. It is possible that information transmission in the identification task involves the same number of translations and same translation rates as the classification task. This hypothesis would lead to the prediction that the higher level of information transmission in the identification task would be totally compensated for by the observed increases in response times, resulting in an information processing rate which is similar to classification.

Table 2

Average Stimulus Information and Information Transmitted (in bits) for Matrix 1 and Matrix 2 as a function of Stimulus:Response Information

Group	Matrix 1 (Identification)		Matrix 2 (Classification)	
	Information Transmitted	Stimulus Information	Information Transmitted	Stimulus Information
4:2	1.773	1.999	.838	.999
8:2	2.505	2.999	.648	.999
8:4	2.814	2.999	1.814	1.999
12:2	3.187	3.457	.750	.999
12:4	3.241	3.457	1.737	1.999

The rate of information processing for Matrix 1 and Matrix 2 is presented in Table 3 as a function of stimulus-response uncertainty conditions. As can be seen, the rate of information processing in the identification tasks is significantly higher, F (1, 25) = 619.46, $p < .001$, than that for the classification tasks. This difference, along with previous data (e.g., Ekel & Teichner, 1979; see Section B; Pollack, 1963), suggests that classification and identification tasks involve different processing stages or translation rates. Further evidence for the difference between classification and identification tasks is provided by differences in the effects of stimulus-response variables within the tasks. The data indicate no consistent difference as a function of stimulus-response uncertainty upon performance in the identification task. The range in information processing rate over information conditions is only .4 bits of information with a rate of 2.5 bits/sec in the 8:4 group and 2.1 bits/sec in the 12:2 group. The data for the classification task, on the other hand, indicate a consistent relationship between the rate of information processing and the number of response categories. The rate of information processing increases with the number of response categories. The interaction between matrix and level of stimulus-response information was significant, F (4, 25) = 13.21, $p < .001$, as was the main effect of stimulus-response information, F (4, 25) = 6.817, $p < .001$.

It should be noted that while there was no effect of stimulus-response information on information transmission rate in the identification task, there was a consistent effect of this variable on the amount of variability in performance. The amount of variability tends to increase with increases in the level of stimulus-response information. Furthermore, variability in the classification task tends to change with response uncertainty. The variation in performance is greater in the four-response than in the two-response

Table 3

Average Information Transmission Rate (in bits/sec) and Standard Deviation (σ) for Matrix 1 and Matrix 2 as a Function of Stimulus:Response Information

Group	Matrix 1 (Identification)		Matrix 2 (Classification)	
	Mean	σ	Mean	σ
4:2	2.172	.417	1.290	.254
8:2	2.235	.476	.788	.121
8:4	2.542	.655	1.937	.375
12:2	2.163	.706	.878	.202
12:4	2.445	.792	1.516	.318

condition. These findings are in accord with the Teichner and Williams model (1979, see Section A). The model postulates that the search through the working memory for stimuli, M:S, and responses, M:R, proceeds in a serial fashion. The fewer the number of stimuli and/or responses included among the set of relevant items, the more quickly they can be searched and the less variability in performance.

Classification and identification tasks such as used in this experiment are complex types of choice reaction time tasks. In order to develop a function to describe reaction time in these tasks we have followed the procedure used by Teichner and Krebs (1974) to describe choice reaction times to simple stimuli. Based on a review of choice reaction time literature, Teichner and Krebs have suggested that response time in a choice reaction time task can be expressed by the formula,

$$CRT = k \log_{10} N_t + a \quad (2)$$

where CRT is choice reaction time, N_t is the number of trials, k is the slope constant, and a is the y intercept. Given an identification task in which a one-to-one translation is required between the number of stimulus alternatives, N_A, and the number of response categories, the slope and intercept constants have been suggested by Teichner and Krebs to be a function of N_A. To examine this possibility, we combined the Matrix 1 data for conditions with the same N_A (8:2 with 8:4 and 12:2 with 12:4) and applied this formula to the data for the present experiment. The resulting functions were:

$$N_A = 4,\ CRT = -256.47 \log_{10} N_t + 1385.03 \quad (2a)$$

$$N_A = 8,\ CRT = -994.97 \log_{10} N_t + 3421.86 \quad (2b)$$

$$N_A = 12,\ CRT = -1173.47 \log_{10} N_t + 4191.49. \quad (2c)$$

In accord with Teichner and Krebs' analysis of less complex CRT tasks, it is clear that both the slope and intercept constants are a function of N_A. Plots

of the intercept constant (a), as a function of N_A and $\log_2 N_A$, are presented in Figure 3a. Figure 3b presents the slope constant (k) also plotted as a function of N_A and $\log_2 N_A$. The curves were fitted by eye. The function describing the logarithmic relationship for the intercept is,

$$a = 1799.33 \log_2 N_A - 2149.63 \quad (3)$$

and for the slope,

$$k = -595.79 \log_2 N_A + 896.63. \quad (4)$$

A similar line of reasoning may be applied to classification tasks in which there is a many-to-few translation. As indicated in our previous analysis, performance in the classification task is a function of both the number of stimulus alternatives, N_A, and the number of response categories, N_R, into which the stimuli are to be classified. Reaction time increases as a function of N_A and N_R. In order to derive a temporal function to describe performance in the classification task, it is necessary to encompass the effects of both of these variables. For the sake of simplicity, we made the assumption that these variables interacted additively to determine performance. Since performance in the identification task indicated a linear relationship of the slope and intercept constants as a function of $\log_2 N_A$, it would be anticipated that a similar linear relationship would exist for the slope and intercept constants as a function of $N_A + N_R$ or $\log_2 (N_A + N_R)$. CRT functions based on Formula 2 were derived for each of the five $N_A + N_R$ conditions from Matrix 2 in this study.

$$N_A + N_R = 4 + 2, \text{ CRT} = -93.83 \log_{10} N_t + 369.92 \quad (2d)$$

$$N_A + N_R = 8 + 2, \text{ CRT} = -341.41 \log_{10} N_t + 1565.34 \quad (2e)$$

$$N_A + N_R = 8 + 4, \text{ CRT} = -322.91 \log_{10} N_t + 1654.21 \quad (2f)$$

$$N_A + N_R = 12 + 2, \text{ CRT} = -472.39 \log_{10} N_t + 1902.54 \quad (2g)$$

$$N_A + N_R = 12 + 4, \text{ CRT} = -572.14 \log_{10} N_t + 2389.45 \quad (2h)$$

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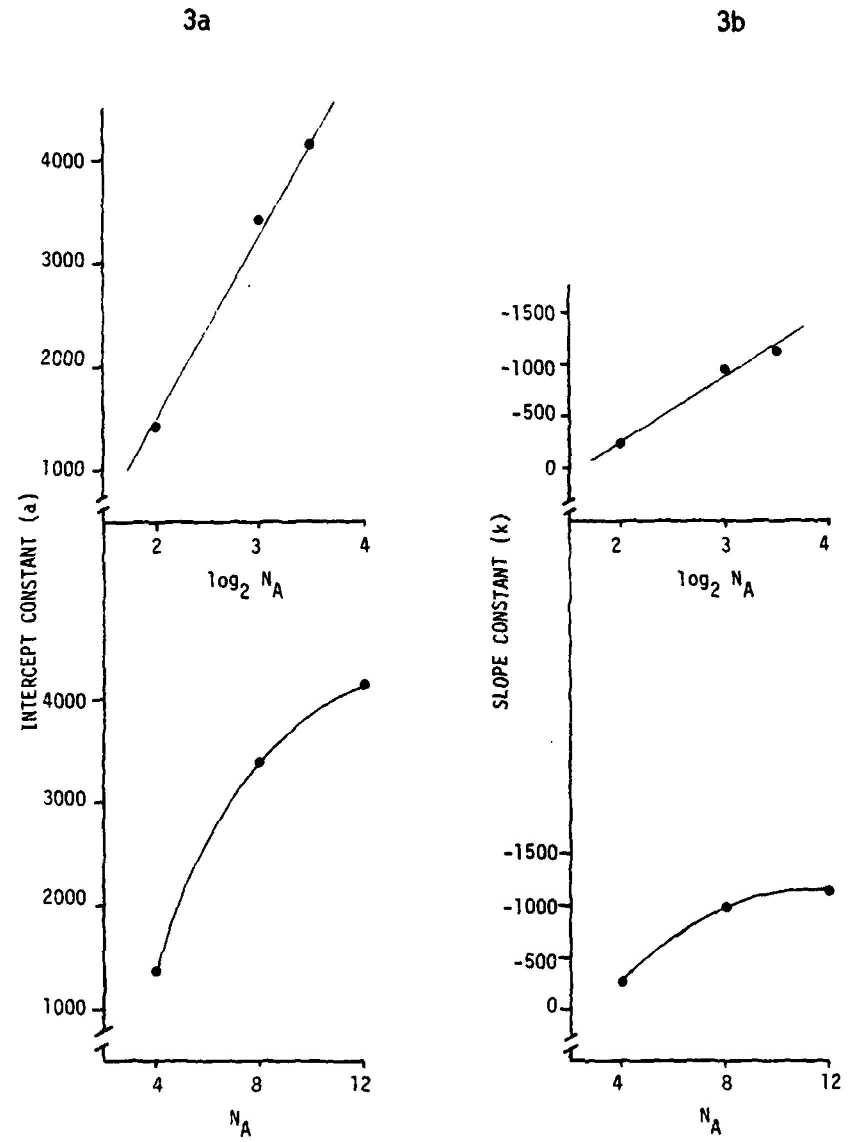

Figure 3. Intercept constants (a) in Figure 3a and slope constants (k) in Figure 3b of Equations 2a-2c as a function of number of stimulus alternatives (N_A) and of $\log_2 N_A$ for the identification task.

The slope and intercept constants are plotted in Figures 4a and 4b as a function of $N_A + N_R$ and $\log_2 (N_A + N_R)$. The curves were fitted by eye. Based on visual inspection, the linear fit of the data points for both $N_A + N_R$ and $\log_2 (N_A + N_R)$ plots is more or less equivalent. In the interest of consistency between the function for the identification and the classification tasks, the $\log_2$ linear function was used. Therefore, the function describing the logarithmic relationship for the intercept is,

$$a = 974.63 \log_2 (N_A + N_R) - 1695.77 \qquad (5)$$

and for the slope,

$$k = -317.03 \log_2 (N_A + N_R) + 736.33. \qquad (6)$$

In a further attempt to examine the differences in the classification and identification tasks to determine if they involve the same or different processes, the identification data from Matrix 1 were plotted along the line of best fit of the intercept and slope functions from the classification data in Figures 4a and 4b. The amount of stimulus-response information in the tasks were handled in the same manner as the classification task and the slopes and intercepts from Formulas 2a, 2b, and 2c were plotted as a function of $\log_2 (N_A + N_R)$. That is, the plots were a function of $\log_2$ of 8, 16, and 24 respectively for the groups with 4, 8, and 12 stimuli. As can be seen, the slope of the points for the $\underline{y}$ intercept and slope constants for the identification task is much steeper than the corresponding data from the classification task. While the identification and classification functions appear to cross at two bits of information or the identification task with four stimuli, these results again suggest differences in the processing stages in the identification and classification tasks.

While all of the data tend to suggest processing differences in the classification and identification tasks, the question of the stage at which this

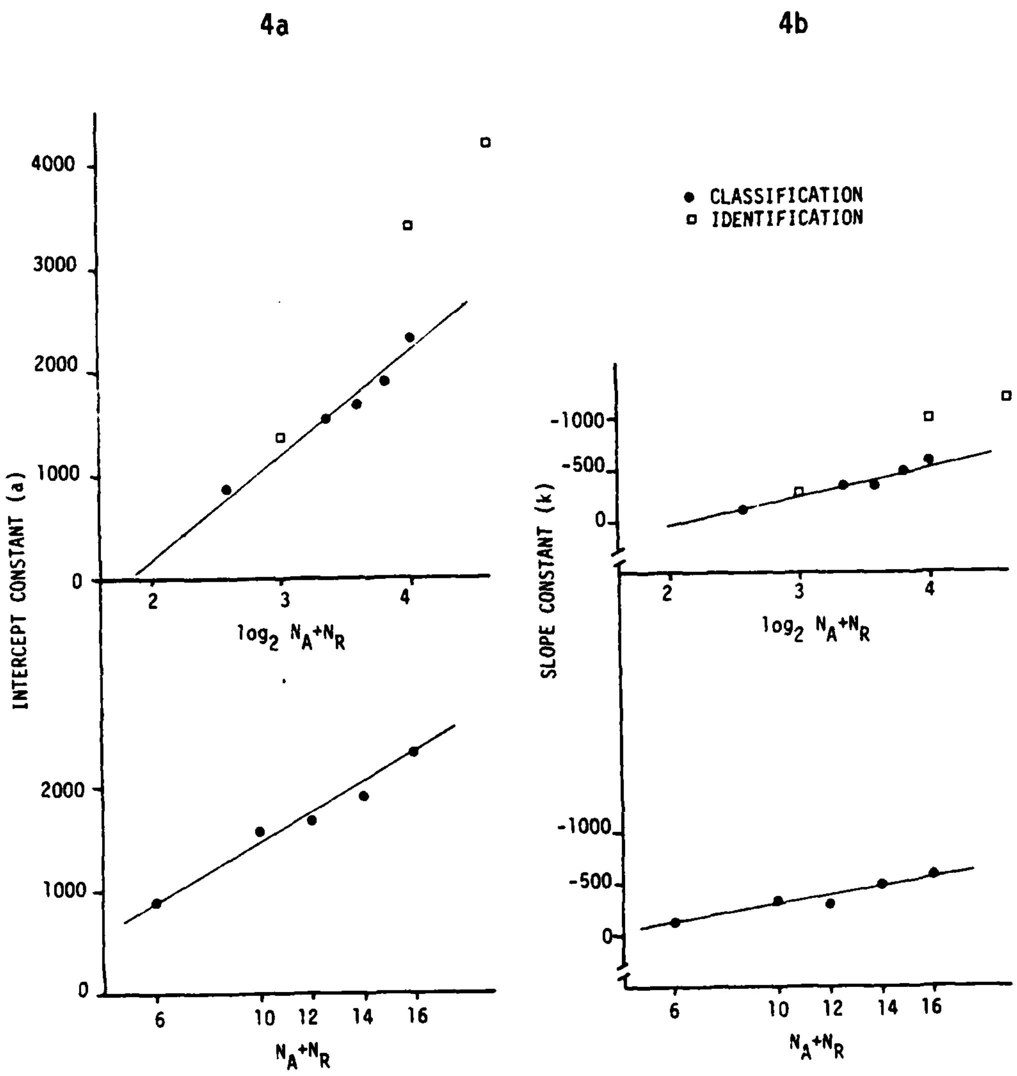

Figure 4. Intercept constants (a) in Figure 4a and slope constants (k) in Figure 4b of Equations 2d-2h as a function of number of stimulus alternatives ($N_A + N_R$) and of $\log_2 (N_A + N_R)$ for the classification task with identification constants superimposed.

difference exists has not been addressed. As suggested earlier, differences in the task may exist at any of five subtask levels. The first subtask level at which it is reasonable to assume potential process difference is in the response criterion (RC) component of the _a_-function.

To examine the different task conditions for potential differences in the RC of the _a_-component, the procedure for establishing RECs, based on Thurstone's scaling techniques (Thurstone, 1925, 1927a, 1927b, 1928) proposed by Grice (Grice, 1968, 1971, 1972a, 1972b, 1977; Grice, Nullmeyer & Spiker, 1976) was used. In applying this technique, the response times for all relevant comparisons were arranged in cumulative probability ($p(R)_{cum}$) distributions with 400 msec intervals. Extreme $p(R)_{cum}$ scores falling in the lower or upper .005 percentiles of the distributions were eliminated. These scores were eliminated as extreme scores have been found to be unreliable and to lead to increased variability in further comparisons. Assuming a normal distribution of the $p(R)_{cum}$, the values were converted to _z_ scores (normal deviates). To verify this assumption the _z_ scores were plotted as a function of the time from stimulus onset. If the $p(R)_{cum}$ distribution is normally distributed then this plot should result in a straight line. All of the _z_ score plots closely approximated straight lines.

Once the normality of the distributions was established the portion of the _z_ distributions for conditions which were to be compared were plotted as a function of one another. Only those _z_ scores which overlapped in terms of time interval from stimulus onset were used. That is, each point on the graphs consisted of the _z_ score for responses which occurred within the same time interval relative to stimulus onset in the _z_ distribution for the two conditions being compared. (For further explanation of this procedure see Section B; and Grice, 1971.)

The curves resulting from plotting the $\underline{z}$ units from the different conditions as a function of one another are known as response evocation characteristic (REC) curves. REC curves can be one of three types. They can be curvilinear, straight line functions with a 45° slope, or straight line functions with slopes of greater than or less than 45°. If the obtained REC curves are curvilinear, then no comparison of the RC can be made as some of the assumptions of the model do not hold for curvilinear data. If the REC is linear and has a 45° slope then the two conditions can be compared with regard to their RC in $\underline{z}$ units. If the REC is linear with a slope of greater than or lesser than 45°, this implies either that the value of d' varies systematically as a function of responsiveness or that d' is constant and that the standard deviations of the two distributions are unequal. The second of the two alternatives is the assumption usually made by Grice (1971) for his model. The existence of unequal standard deviations for the two distributions being compared make the data meaningless. Unless the values of the two distributions are in the same units the relative RC for the two conditions cannot be determined. Since the ratio of the standard deviations are given by the slope of the REC, it is possible to choose the standard deviation of either distribution as the working unit and to convert the values of the other condition to this unit. The values on one distribution can be converted to units of the other by dividing each value by the slope of the best fitting line determined by linear regression. Once the data have been converted then comparisons in the RC can be made. Once the REC curves have a slope of 40° then their intercept or displacement from the main diagonal provide a measure of the difference in the average RC.

To determine if there was a possible RC difference as a function of the number of stimuli and responses, the data from Matrix 1 were compared. Responses to Matrix 1 involved an identification or a one-to-one correspondence

between stimuli and responses. RECs were obtained by individually comparing conditions with 4:2 and 12:2 stimuli:responses with the condition in which there were 8:2 stimuli:responses. The 12:2 and 8:2 conditions were chosen for comparison as these groups would later receive classification tasks with the same number of categories. All plots yielded linear RECs, however, the plots did not have slopes of 45° or 1. The slope of the 4:2 curve relative to 8:2 was 1.15 while the slope resulting from the 12:2 comparison was 1.05. Using the standard deviation of the 8:2 group as the working unit, all curves were transformed into standard deviation units of this group. The plot of this transformed data is presented in Figure 5. As can be seen, the RC is related to the amount of stimulus-response uncertainty. The fewer the number of possible stimuli-responses present in the task, the lower the corresponding RC. The RC of the 4:2 condition was .9 $\underline{z}$ units lower than the RC for the 8:2 condition, and the 12:2 condition had an RC of .5 $\underline{z}$ units higher than the 8:2 condition.

This difference in RC may have been due to differences caused by the number of stimuli or due to differences caused by the number of responses; which of these factors is, or whether both are contributing to RC cannot be determined by the above comparison. In order to examine the effects on RC of the number of stimuli, it is necessary to vary the number of stimulus items while holding the number of responses constant. Two such comparisons were made. One held the number of responses to 2 while varying the number of stimuli from 4 to 8 to 12; i.e., comparison of the Matrix 2 data for conditions 4:2, 8:2, and 12:2. The second of these comparisons held responses to 4 while again varying the number of stimuli from 4 to 8 to 12; i.e., comparison of the Matrix 1 data for condition 4:2 (4 stimuli:4 responses) and the Matrix 2 data for conditions 8:4 and 12:4. The resulting RECs for all comparisons were

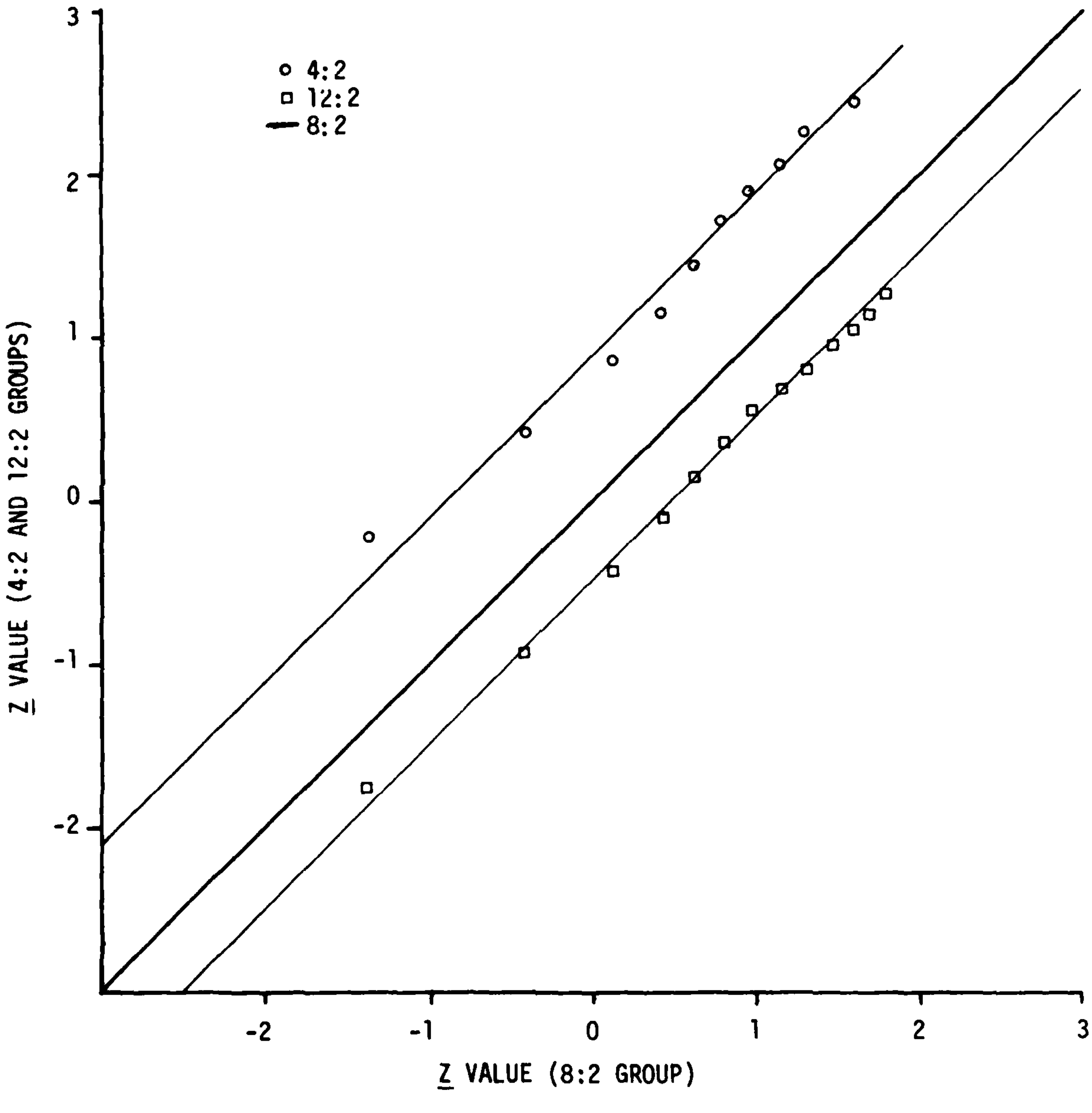

Figure 5. Transformed REC plots for the 4:2, 12:2, and 8:2 stimulus-response conditions in the identification task (Matrix 1). Data from all groups have been plotted in comparison and in standard deviation units of the 8:2 group.

transformed and the plots of the transformed data are presented in Figure 6. In Figure 6a the standard deviation for the 8:2 condition was used as the working unit and the data from the 4:2 and 12:2 groups were transformed to this unit. As can be seen, the RC can be said to vary with the number of stimuli. Given two responses, the RC for 4 stimuli is .77 units less than that for 8 stimuli and 1.02 units less than that for 12 stimuli. The data from Figure 6b were transformed to provide standard deviation units equivalent to the Matrix 2, 8:4 data. These data also indicate a difference in RC with the number of stimuli. When the condition in which there are 4 stimuli and four responses is compared with the 8:4 condition, there is a .45 difference in RC while the 12:4 condition has an RC of .65 units higher than the 8:4 condition. These results indicate that the RC is affected by the amount of stimulus information. When response uncertainty is held constant, the RC increases with increases in stimulus information.

The differences in response criterion are not directly comparable across graphs as one is in standard deviation units associated with the 8:2 condition and one is in units associated with the 8:4 condition. Nevertheless, the increase in RC between the 4-stimulus and the 8-stimulus condition with two responses was substantially greater than between the 8- and 12-stimulus conditions, .77 as compared to .25 units. In the four-response comparisons, the 4 to 8 stimulus difference is smaller than the 8 to 12 difference. This difference in magnitude as a function of number of responses may be due to differences in the type of task associated with the 4:4 stimulus-response information condition. This condition involved an identification task while the other comparisons involved classification tasks. This explanation would necessitate that identification tasks have a higher RC than classification tasks, thus decreasing the difference between the 4:4 and 8:4 comparison. This explanation is supported

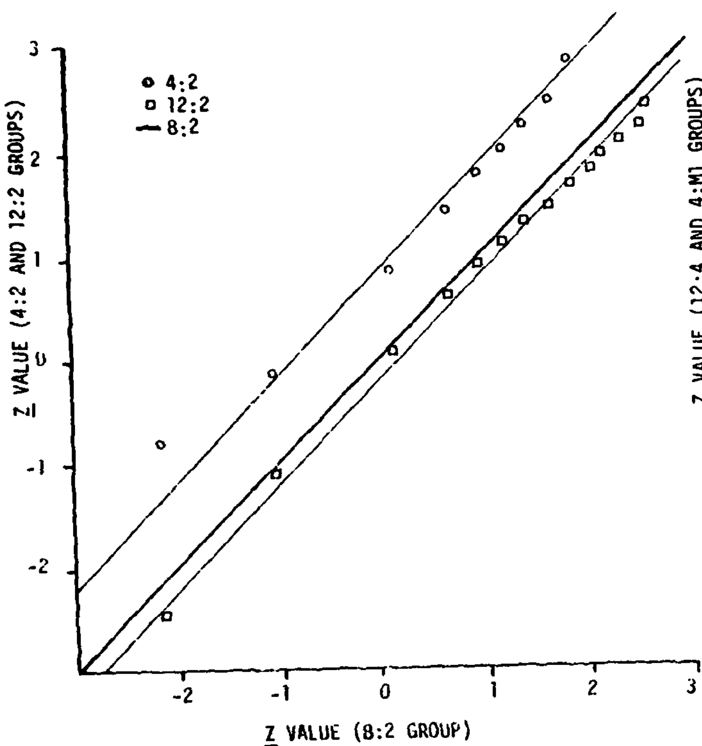

Figure 6a. Transformed REC plots for the stimulus-response conditions 4:2, 12:2, and 8:2 in the classification task (Matrix 2). Data are plotted in comparison and in standard deviation units of the 8:2 group.

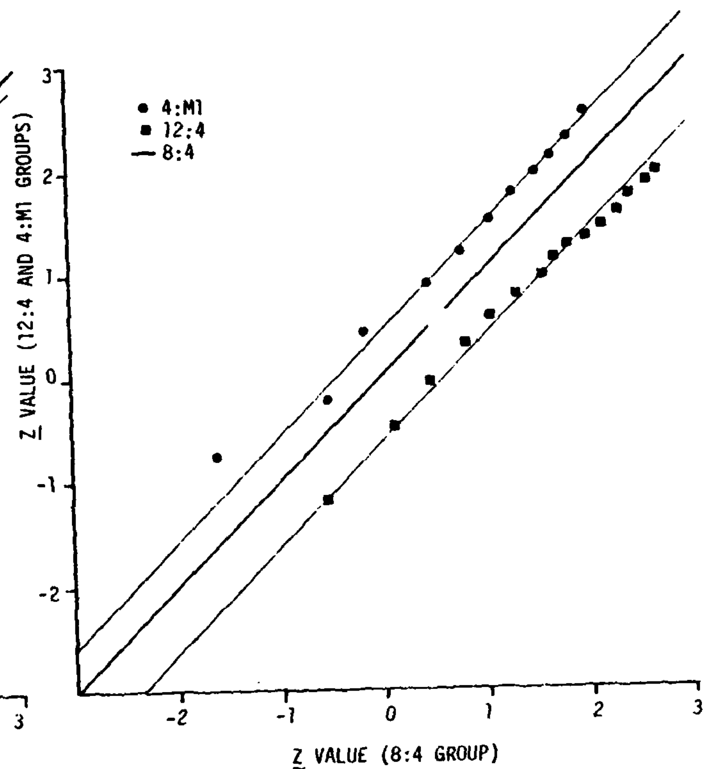

Figure 6b. Transformed REC plots for the identification (Matrix 1) data for stimulus-response condition 4:2 and the classification data (Matrix 2) for stimulus-response conditions 8:4 and 12:4. Data are plotted in comparison and in standard deviation units of the 8:4 group.

by the data of Ekel and Teichner (1979; see Section 2) which suggests that classification tasks have lower RCs than identification tasks. Acceptance of this hypothesis along with the data of Ekel and Teichner (1979) suggests that the difference between identification and classification tasks in RC cannot explained in terms of the amount of stimulus information or number of items per category.

A second possible explanation of differences between the RC for the different groups in Figures 5a and 5b is that the differences in RC as a function of the number of stimulu vary as a function of the number of responses. In order to determine if the level of response uncertainty affects the RC, the RECs for conditions with identical stimulus information were plotted in comparison with conditions varying in response uncertainty. These comparisons required the plotting of the Matrix 2, 4:2 data against the Matrix 1, 4:2 data (4 stimuli:4 responses); the Matrix 2, 8:2 data against the Matrix 2, 8:4 data; and the Matrix 2, 12:2 data against the Matrix 2, 12:4 data. The initial RECs were linear with slopes greater than 1. These data were transformed into the standard deviation units of the two response conditions in Figure 7. While the data from these three plots are not directly comparable due to possible differences in standard deviation units, it is interesting to note that when the number of stimuli is held constant, the difference in RC between conditions involving tow or four responses is essentially the same. The best fitting lines for all three comparisons fall one on top of another. The resulting RCs calculated from these plots indicate a .90 increase in RC when response categories increase from two to four. These differences in RC suggest the possibility that changes in response uncertainty result in an effect upon RC which independent of the number of stimuli to be placed in each category. This finding is in accord with that of Pollack (1963) indicating

that classification time was influenced more by the number of response categories than by the number of examples per category.

A third variable other than amount of stimulus or response uncertainty which has been suggested to influence information processing in a classification task is the amount of information reduction which occurs in going from many to few categories (Posner, 1964). Posner has suggested that with speeding of response task difficulty is an increasing linear function of the amount of information reduced in placing stimuli in categories; i.e., if stimulus information is held constant the amount of information reduction increases with decreasing response categories. These findings suggest the possibility that there may be response criterion differences as a function of information reduction. In order to examine this possibility, RECs for the Matrix 2 data were obtained for all conditions as a function of the 4:2 condition. The resulting curves were linear with all curves having slopes greater than 1. The data for all conditions were transformed into standard deviation units of the 4:2 condition and the resulting RECs are presented in Figure 8. If the RC were a function of the amount of information reduction, it would be expected that the RECs for the different conditions would be ordered in terms of information reduction. The hypothesized ordering would be 4:2, 8:4, 8:2, 12:4, and 12:2 with corresponding information reductions of 2, 4, 6, 8, and 10. As can be seen in Figure 8, the hypothesized ordering was not found. The ordering of the conditions indicates no observable effect of information reduction or the number of items per response category.

In conclusion, even though the standard deviation units may be different in the RECs presented in Figure 7, these findings would imply that changes in RC as a function of the number of responses is not only the same across different stimulus levels, but is unaffected by whether the change is from an

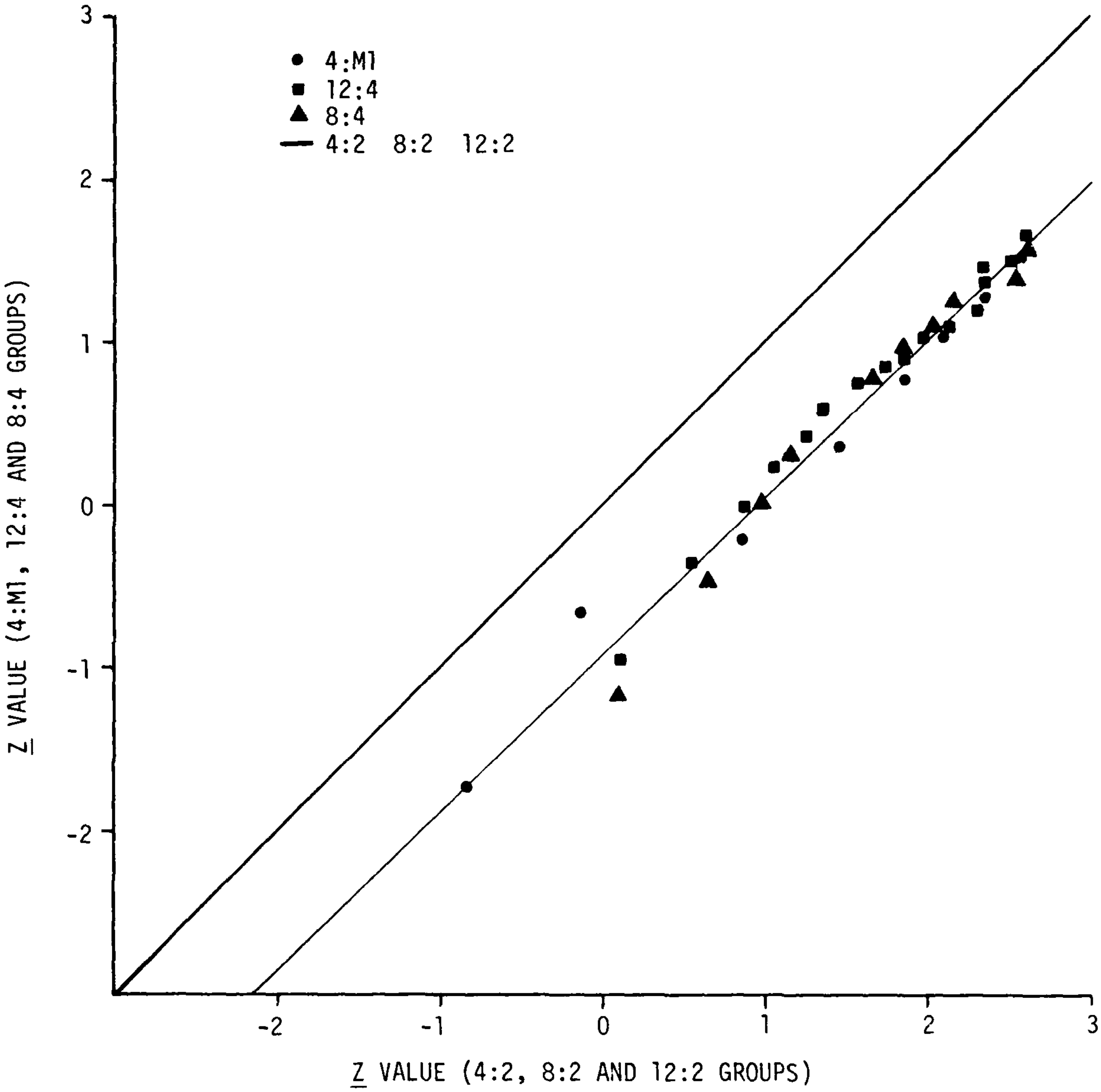

Figure 7. Transformed REC plots for the Matrix 1, 4:2 group in comparison with the Matrix 2, 4:2 group; the Matrix 2, 8:4 group in comparison with the Matrix 2, 8:2 group; and the Matrix 2, 12:4 group in comparison with the Matrix 2, 12:2 group. All data have been plotted in standard deviation units of the two response groups.

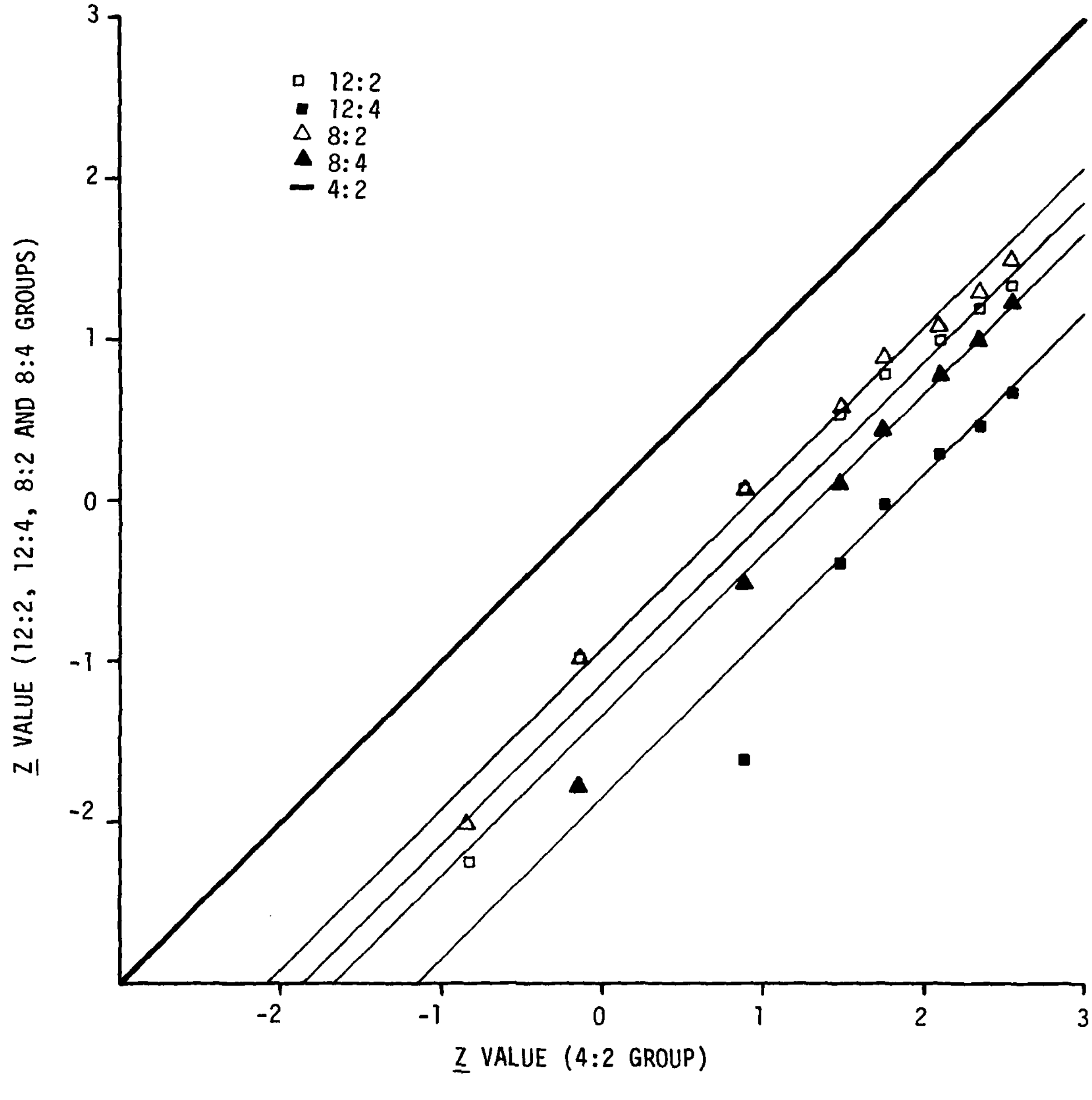

Figure 8. Classification data (Matrix 2) for the 12:2, 12:4, 8:2, and 8:4 stimulus-response groups plotted in comparison and in standard deviation units of the 4:2 group.

identification to a classification task or from one level of classification to another level. These data, therefore, would suggest that the major RC difference between identification and classification results from the number of potential response categories rather than other aspects of the tasks. Whether the major differences in RCs between the classification and identification task are due to processing time differences associated with the process of making a one-to-one translation as compared to a many-to-few translation can only be determined by comparing identification and classification tasks with the same number of response categories. The existence of differences in classification and identification tasks beyond what can be accounted for by RC and the number of response alternatives is suggested in Figure 4a and 4b. These plots of functions relating N_A and N_R to response time demonstrate that differences in identification and classification are evident even when the number of stimulus and response alternatives are taken into account.

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Appendix A: Table A

Distribution Statistics for Error-Free Trials for Individual Subjects as a Function of Task and Stimulus Response Information

Subject	Matrix	Number of Trials	Median (in msec)	Range (in msec) High	Range (in msec) Low	Mean (in msec)	Standard Deviation (in msec)
1	1	312	904	4166	665	1081.40	490.02
	2	313	839	2559	181	917.35	276.90
2	1	311	810	3883	575	923.27	368.63
	2	313	734	2539	548	785.06	211.74
3	1	313	1025	4159	650	1199.13	475.92
	2	307	919	2331	612	1025.80	319.11
4	1	316	1054	3710	791	1242.24	480.58
	2	313	904	4298	290	1037.93	418.43
5	1	318	1348	6829	933	1608.50	697.23
	2	317	1169	3071	871	1262.68	313.16
6	1	311	838	4439	579	1048.17	496.88
	2	307	745	2712	501	812.76	251.35
7	1	319	1069	3500	662	1243.60	502.51
	2	316	748.5	2725	528	853.52	297.70
8	1	316	1342	4404	726	1534.59	677.03
	2	312	867.5	2275	499	941.09	304.31
9	1	318	954	3456	726	1062.03	356.59
	2	317	793	5785	610	845.16	322.22
10	1	270	848.5	1792	632	912.19	216.86
	2	234	661	2163	435	708.46	210.32
11	1	314	981.5	8401	706	1205.42	633.70
	2	307	737	3079	526	865.06	341.67
12	1	242	966	2572	588	1096.15	368.45
	2	271	763	1802	585	856.98	226.66
13	1	319	1075	5701	745	1278.63	643.71
	2	320	890.5	5751	642	1043.22	474.78
14	1	292	894.5	3113	603	1034.38	396.05
	2	302	1031.5	5162	654	1302.62	749.18
15	1	306	1459	6178	668	1713.91	891.77
	2	317	1297	4132	729	1502.79	662.39
16	1	314	1384.5	7086	737	1822.39	1156.11
	2	316	1010.5	3526	707	1157.51	414.78

Table A Continued

Subject	Matrix	Number of Trials	Median (in msec)	Range (in msec) High	Range (in msec) Low	Mean (in msec)	Standard Deviation (in msec)
17	1	311	1228	7736	774	1549.21	921.12
	2	315	1144	9823	750	1356.48	733.20
18	1	309	1063	6451	736	1343.16	778.44
	2	312	865	6268	657	1006.15	448.12
19	1	311	1363	6641	752	1720.33	1037.94
	2	313	692	2441	370	732.40	208.18
20	1	308	1389	8237	756	1798.36	1136.80
	2	310	806	5602	586	932.86	420.07
21	1	317	1225	7032	776	1600.10	1013.73
	2	317	745	6121	539	944.05	604.50
22	1	291	926	4655	628	1146.36	632.91
	2	311	669	2074	455	699.99	166.84
23	1	303	1186	5641	726	1560.66	950.98
	2	304	782.5	4304	438	873.81	314.95
24	1	313	1602	9755	886	2024.91	1131.36
	2	315	1079	4459	733	1248.88	540.42
25	1	313	877	7567	645	939.61	421.42
	2	310	712	1470	478	752.00	156.10
26	1	315	855	1805	610	903.13	180.13
	2	309	764	2207	617	804.48	172.02
27	1	313	634	1905	444	689.54	181.29
	2	307	467	1024	319	493.90	109.99
28	1	306	624	1841	509	648.20	124.67
	2	305	538	915	348	544.79	74.22
29	1	306	890	2097	617	937.29	193.12
	2	305	709	1584	483	740.93	143.29
30	1	314	873	1909	650	952.65	229.33
	2	309	678	1202	548	695.16	87.10

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ON THE RELATION BETWEEN THE JUDGMENTAL TASKS OF TEMPORAL ORDER AND FUSION-NONFUSION

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The limitation of the human operator to extract order, fusion and nonfusion information from two dichotically presented auditory stimuli is well documented (Babkoff, 1975; Babkoff & Sutton, 1966; Cheatham & White, 1954; Corso, 1976, 1978; Hirsh, 1969; Hirsh & Sherrick, 1961; Kristofferson, 1963). This limitation is a function of the interval between the onset of the two stimuli. If the onset interval is less than 20 msec, then the temporal order of the two stimuli cannot be determined (Hirsh & Sherrick, 1961; Corso, 1976); however, if the onset interval is greater than 10 msec then two nonfused stimuli will be perceived (Fraisse, 1963; Corso, 1976). Intervals less than 10 msec will result in the perception of one fused stimulus (Fraisse, 1963; Corso, 1976).

Less well known, however, are the dependencies and relations between the judgmental tasks of order and fusion-nonfusion. This lack of knowledge appears to have resulted from using accuracy and threshold measures rather than latency measures. That is to say that variations in the latency of temporal order and fusion-nonfusion judgments, when coupled with accuracy data, may provide information about the nature of the processing sequency between those types of judgmental tasks.

Additionally, most investigators dealing with temporal order and fusion-nonfusion judgments are not factorial. Consequently, interactions between temporal order and fusion-nonfusion as a function of various stimulus parameters are not considered. Those interactions may provide additional knowledge about the processes and relations between temporal order and fusion-nonfusion judgmental tasks.

Therefore the intent of this investigation was to: (a) examine the relation between temporal order and fusion-nonfusion tasks through latency and accuracy measures; (b) examine the factorial influence of stimulus parameters on temporal order and fusion-nonfusion tasks; and, (c) integrate the judgmental tasks of order and fusion-nonfusion into one theoretical framework.

The Experiment

This experiment was designed to investigate the relation between judgments of order and judgments of fusion-nonfusion. The latency data in conjunction with the accuracy data should reflect the internal information flow required for fusion-nonfusion and order judgments. That is, if temporal order judgments require information about fusion-nonfusion judgments then:

1. The accuracy data should reflect an interaction between the two judgmental tasks and stimulus onset asynchrony (SOA). This interaction should manifest itself as an increase in the number of correct fusion-nonfusion task judgments. Additionally, the number of correct fusion-nonfusion task judgments should be significantly greater than the number of temporal order task judgments for each SOA value.

2. The latencies associated with the temporal order task should be greater than the latencies associated with the fusion-nonfusion task for each SOA value.

Additionally, this experiment was designed to investigate the influence of stimulus intensity on the latency and accuracy on the judgmental tasks. Since increases in stimulus intensity have been linked to decreases in simple response latency (Teichner & Krebs, 1972); if the latency of order and fusion-nonfusion judgments are related to stimulus intensity, then simple reaction time, judgments of fusion-nonfusion and judgments of temporal order could be incorporated into the same model.

Unfortunately the influence of stimulus intensity on the latency of those types of judgments is unknown. With reference to the influence of stimulus intensity on the accuracy measure; as intensity increases, the amount of time between the onset of the two stimuli decreases for the same number of nonfusion responses (Fraisse, 1963). That is, as stimulus intensity increases, the fusion-nonfusion threshold decreases. The data on the influence of stimulus intensity for the temporal order threshold is conflicting (Corso, 1976, 1978; Rutschmann, 1973). Hirsh and Sherrick (1961) provide evidence suggesting that stimulus intensity does not alter the temporal order threshold; however, Rutschmann (1973) has provided evidence to the contrary.

Consequently, this experiment will provide data relating stimulus intensity to the latency and accuracy of temporal order and fusion-nonfusion task judgments; data that is either missing from the literature or is nonconclusive.

Method

Subjects. Six male and fourteen female student volunteers from introductory psychology classes served as subjects. Three male and seven female subjects were randomly assigned to one of two groups. The subjects were required to possess an absolute auditory threshold of at least 20 dB SPL (sound pressure level) at the frequencies of 500 CPS (cyles per second), 1000 CPS, 2000 CPS, 4000 CPS and 8000 CPS. Furthermore, the subjects were required to be right-handed, English speaking and between the ages of 18 and 30 years. The subjects served in one, two-hour session.

Apparatus. A specially designed and constructed apparatus was used in this experiment. The apparatus generated a 1000 CPS pure-tone sine wave, controlled the duration, rise and fall times, attentuation and the SOA values for a pair of tones through a digital entry keyboard. Furthermore, the apparatus contained two millisecond response timers and two response indicators.

The auditory stimuli were presented to the subject through a matched and calibrated set of Grason-Stadler earphones, model number TDH-49, fitted with a MX-41/AR cushion. Each side of the headset contained a set of positive and negative leads for the specific purpose of utilizing a dichotic stimulus presentation.

The frequency of the signal was calibrated using a Hewlett-Packard digital counter, model number 5302A. The intensity of the signal was calibrated with a Bruel and Kjaer Precision Sound Level Meter, model number 2203, and a Bruel and Kjaer Artificial Ear, model number 4152, fitted with a T4131 condensor microphone.

The response panel contained a home key and two response keys as well as a warning light. Depending on the experimental condition, the two response keys designated the right ear and the left ear for the temporal order task, or they designated fusion and nonfusion for the fusion task.

The subject's station was situated in a sound-deaded chamber. All experimental apparatus, with the exception of the response panel, was situated in an adjacent room. Viewing of the subject was possible through a one-way mirror.

Design. The judgmental task, temporal order or fusion-nonfusion, was the between-subject variable. Stimulus onset asynchrony and stimulus intensity were the within-subject variables. The dependent variables were the number of correct responses and response latency.

The intensity of the 1000 CPS dichotically presented stimulus pairs were 70 dB SPL, 55 dB SPL and 40 dB SPL (re .0002 dynes per cm^2). Each stimulus within the stimulus pair assumed a constant 20-msec duration with a 10-msec rise and fall time. Stimulus onset asynchrony assumed values of 0 msec, 1 msec, 2 msec, and 4 msec to 28 msec in 4-msec steps, for a total of 10 SOA values.

Prior to the onset of the stimulus pair was the occurrence of a warning light. The onset of the warning light occurred 200 msec to 700 msec in 100-msec steps prior to the onset of the first stimulus in the stimulus pair. The duration of the warning light was 500 msec.

The 10 SOA values were combined with the three intensity values so that each SOA value occurred with each intensity value. Furthermore, the initial stimulus of the stimulus pair was randomly presented to the right ear on one half of the trials and to the left ear on the other half of the trials. The intensity by SOA by ear combinations were randomly presented to each subject. Given the completely randomized design, a total of 60 judgments were required from each subject. Additionally, there were five replications of the factorial design for a total of 360 trials per subject.

Procedure. Initially, each subject was screened for normal hearing with a Tracor Clinical Audiometer, model number 115A. After the screening session, each subject performed a simple reaction time task to a 1000-CPS dichotically presented auditory stimulus. The intensity of the stimulus assumed values of 70 dB SPL, 55 dB SPL and 40 dB SPL. For the first 75 trials the subject responded by depressing only the left or only the right key. On the remaining 75 trials the other response key was used. Upon completion of the simple reaction time task a five-minute rest period occurred.

In the final portion of the experiment each subject was required to perform one of the following tasks:

1. In the fusion task, the subjects were required to report the perception of one or two stimuli when a pair of dichotic stimuli was presented. Fusion was defined as the report of one stimulus; nonfusion was defined as the report of two stimuli. The response was performed by releasing the home key and depressing one of the two response keys to designate the number of stimuli

perceived. After depressing the response key, the subject returned to the home key and depressed that key until the next trial.

2. In the temporal order task, the subjects were required to identify the order of occurrence of the dichotic stimuli by deciding whether the stimulus occurred first in the right or left ear. The response for this task was performed in exactly the same manner as in the fusion task, but the two keys were designated as to indicate the right and left ears.

The subjects in each group used the index finger of the right hand to perform the response and the same response panel. As a result, the response times for both groups were expected to be comparable.

Results

Simple reaction time. The mean simple reaction time data obtained during the simple reaction time portion of the experiment was subjected to a repeated measures analysis of variance. The intent of this analysis was to determine that no reaction time differences between the two groups existed and that no response bias for the right and left keys existed. No significant difference between the fusion-task and temporal-order-task subjects was observed. Furthermore, the difference between the right and left keys was not significant. However, the main effect of stimulus intensity was significant, $F\ (2, 36) = 4.09$, $p < .05$. A Least-Significant-Difference test of the three intensity values showed that the only significant difference occurred between the 40 dB, and the 55 dB and 70 dB intensity values. No significant interactions were observed.

Response time for the fusion and temporal order tasks. The median response time across the 12, intensity by SOA, replications (collapsed over the ear of the initial stimulus presentation) for each subject, was subjected to a mixed design analysis of variance. Figure 1 presents the significant

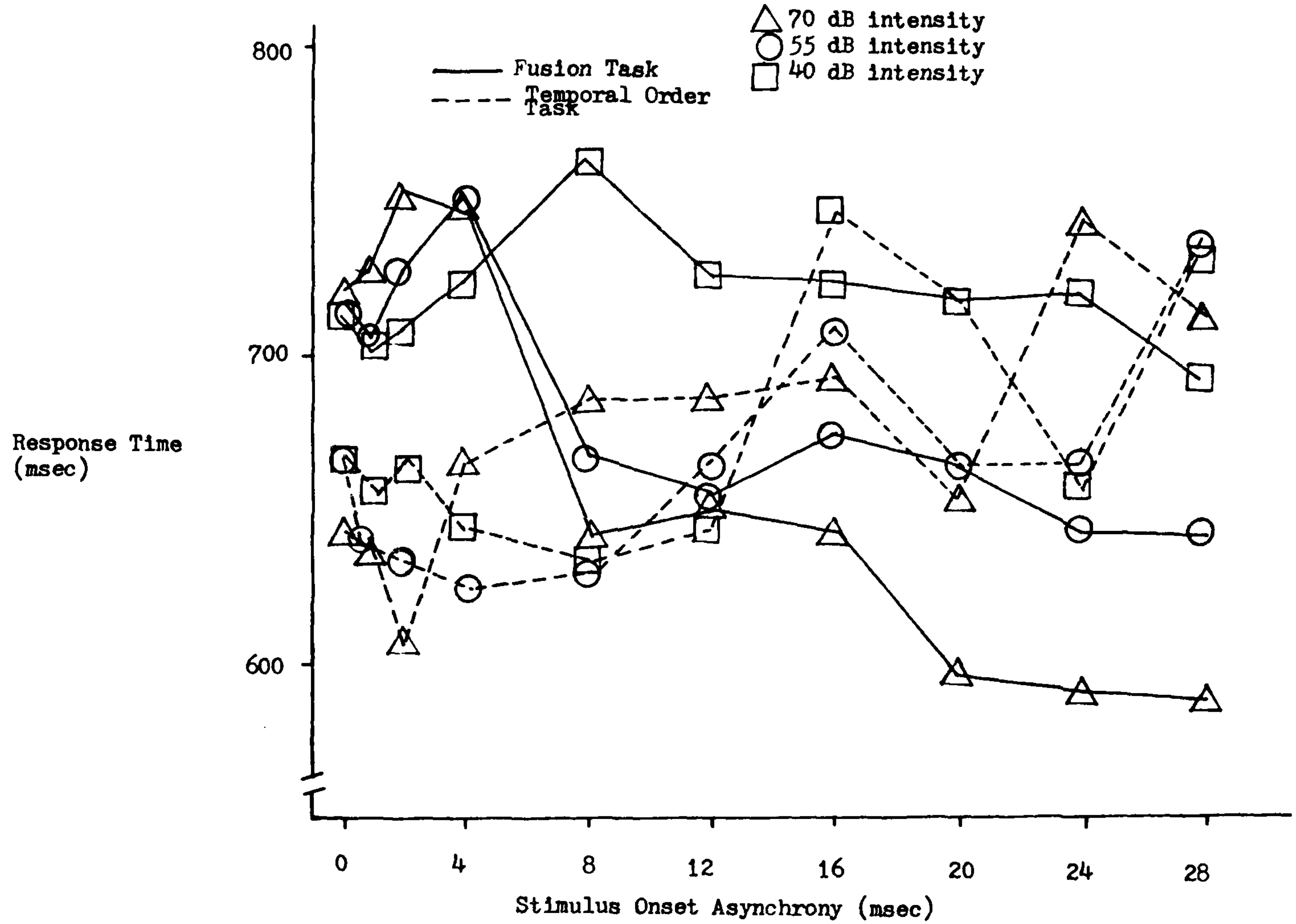

Figure 1. The significant intensity by SOA by task interaction.

intensity by SOA by task interaction [F (18, 384) = 3.47, p < .01]. Also observed were significant task by SOA and intensity by SOA interactions, F (18, 324) = 1.91, p < .01 respectively.

An evaluation of the three-way interaction was performed to assess the significant differences between the two tasks for the same intensity level across the SOA values. This evaluation showed that at the 70-dB intensity value the two tasks were significantly different for SOA values of 0, 1, 2, and 4 msec, with the temporal order task requiring less time. No significant differences between the two tasks for the SOA values of 8 to and including 16 msec were observed. For SOA values greater than 16 msec, the temporal order task required significantly more time than the fusion task.

For the 55 dB intensity value, the 0-msec SOA value resulted in no significant differences between the two tasks. With SOA values of 1, 2, and 4 msec, the fusion task required more time than the temporal order task. For SOA values equal to or greater than 8 msec, but less than 24 msec, no significant differences between the tasks were observed. The two tasks were significantly different at the 28-msec SOA value, with the temporal order task requiring more time.

In a similar manner, for the 40 dB intensity value, SOA values of 0 and 1 msec resulted in no significant differences between the tasks. With SOA values greater than or equal to 2 msec, but less than 16 msec, more time was required for the fusion task than for the temporal order task. Stimulus onset asynchrony values of 16 and 20 msec resulted in no significant task differences. The 24-msec SOA value resulted in the fusion task requiring significantly more time than the temporal order task. No significant differences between the two tasks for the 28-msec SOA value were observed.

<u>Response time for the fusion task</u>. Since the analysis of variance for the response time data for both the fusion and temporal order tasks yielded significant two- and three-way interactions which are not readily interpretable, two additional analyses were performed to provide separate information about each task. For the fusion task, a repeated measures analysis of variance was performed on the median response time.

This analysis showed taht the main effects of intensity, SOA and the intensity by SOA interaction were significant, $\underline{F}$ (2, 18) = 14.15, $\underline{p} < .01$, $\underline{F}$ (9, 81) = 5.29, $\underline{p} < .01$ and $\underline{F}$ (18, 162) = 4.79, $\underline{p} < .01$. The two-way interaction, presented in Figure 2, and an evaluation of that interaction suggests that the intensity effect occurs at different SOA values. For SOA values of 0, 1, 2, and 4 msec there is no difference between the intensity values. At the 8-, 12- and 16-msec SOA values, the 40-dB intensity level was significantly different from both the 55-dB intensity level and the 70-dB intensity level. With SOA values greater than 20 msec, all three intensity levels are significantly different.

A further analysis was performed on the SOA values for each intensity level. This analysis of all pairwise comparisons for the 70-dB intensity level, showed that the onset values of 0, 1, 2, and 4 msec were significantly different from the remaining SOA values. For the 55-dB intensity level, the 0-msec SOA value was significantly different from the 24- and 28-msec SOA values, and the 4-msec SOA value was significantly different from all larger SOA values. For the 40-dB intensity level no significant SOA differences were observed.

<u>Response time for the temporal order task</u>. The median response time for the temporal order task was subjected to a repeated measures analysis of variance. No significant main effects or interactions were observed.

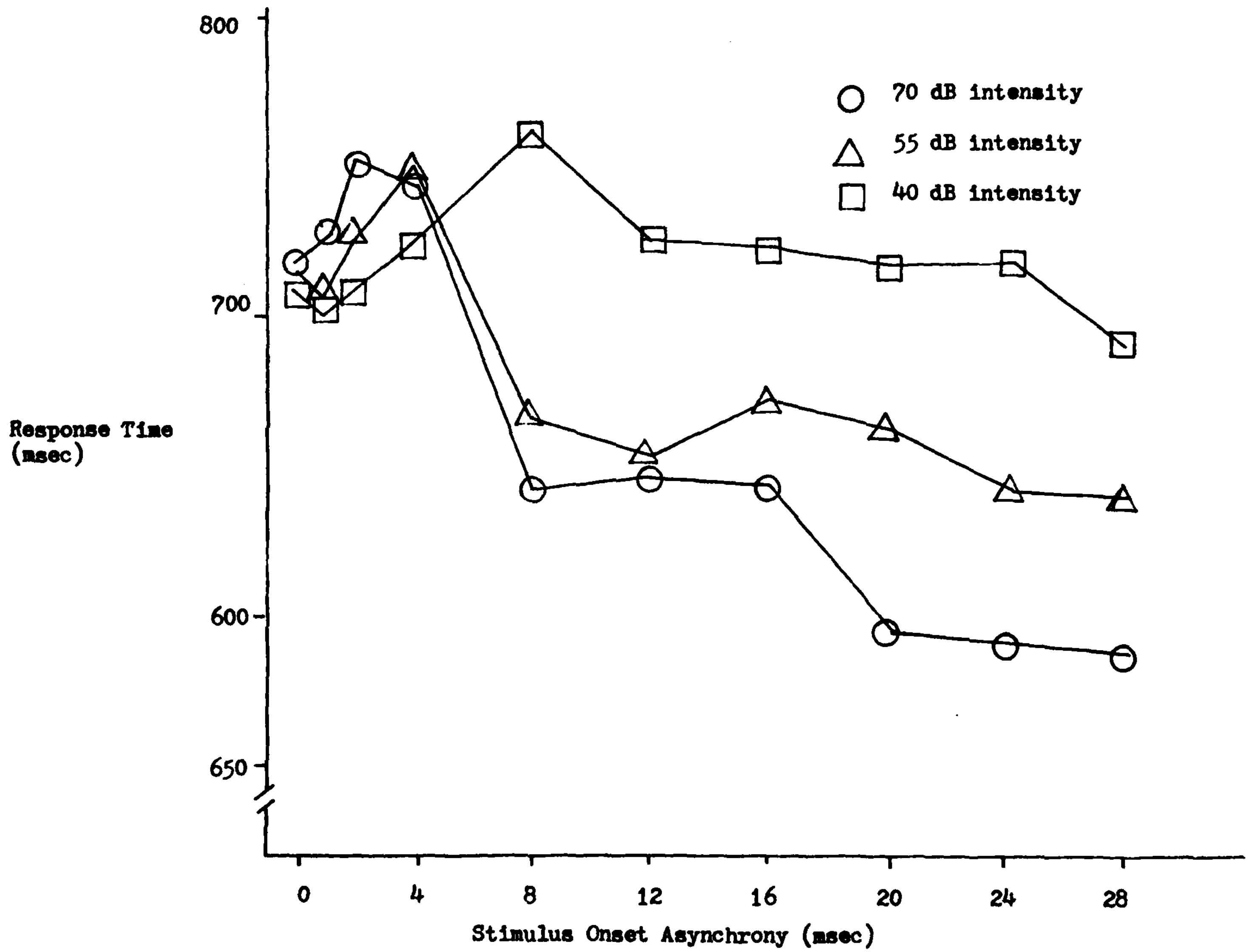

Figure 2. The significant intensity by SOA interaction for the fusion task.

Accuracy for temporal order and fusion tasks. The number of correct responses for each subject, summed across the 12 intensity by SOA replications was subjected to a mixed disign analysis of variance. For those trials where the SOA value was 0 msec, the responses were excluded from the analysis.

The results of the analysis showed a significant main effect for intensity, F (2, 36) = 10.72, p < .01 and a significant main effect for SOA, F (8, 144) = 66.66, p < .01. Additionally, significant intensity by task, SOA by task and intensity by task interactions were observed, F (2, 36) = 6.14, p < .01, F (8, 144) = 53.01, p < .01 and F (16, 288) = 2.95, p < .01 respectively.

The three-way interaction, presented in Figure 3, shows an increase in the number of correct judgments for the fusion task as SOA increases. Additionally, the number of correct judgments for the fusion task is significantly affected by stimulus intensity when the SOA is greater than 4 msec. The number of correct temporal order judgments shows a rather pronounced (and significant) influence of intensity at the 2-msec SOA value. Other than the increase in the number of correct judgments from 1 to 2 msec, and the convergence of the function at 4 msec, the number of correct judgments is constant for intensity and SOA, at least to the 28-msec SOA value.

Threshold analysis. The threshold for the three intensity values was subjected to an analysis of variance. The SOA value that resulted in 75% correct responses for each subject and intensity was selected as the threshold for each task. It can be seen from Figure 3 that across all subjects in the temporal order task, only the threshold values for the fusion task were subjected to the analysis. The main effect of intensity was significant, F (2, 18) = 10.28, p < .01. As the intensity increased, the threshold decreased; 15.5-, 11.5-, and 7.8-msec threshold values for the 40-dB, 55-dB, and 70-dB intensity values, respectively.

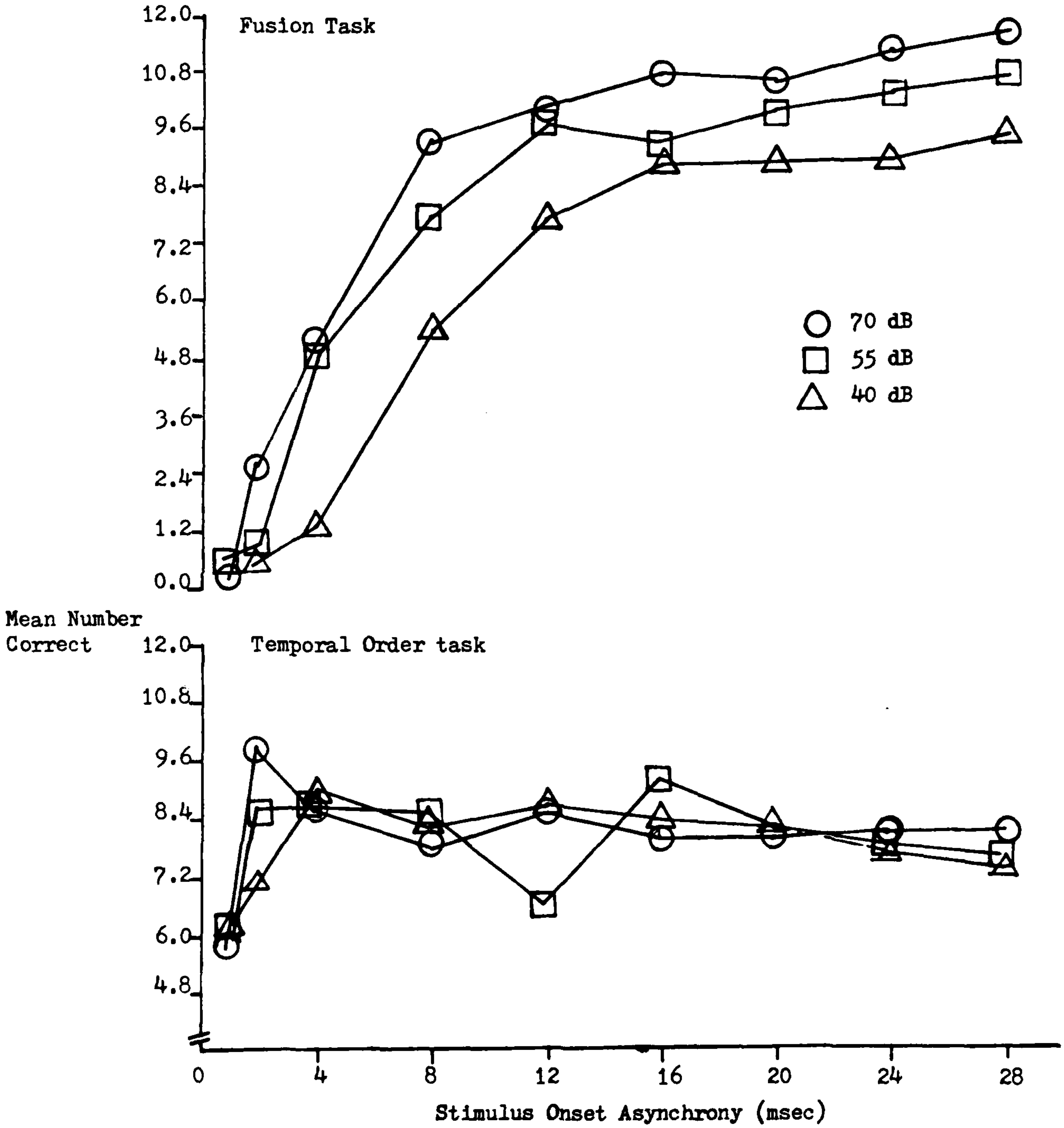

Figure 3. The significant intensity by task by SOA interaction.

Discussion

The results of this experiment suggest several interesting findings. First, with respect to the latency data, there is a trend that shows the temporal order task to require less time, then an equal amount of time, and then more time to perform than the fusion task. Implicit to this finding is the notion that the temporal order task requires and does not require information from the fusion task.

Second, stimulus intensity initially has no role in fusion task judgments, until an SOA of about 4 msec, at which time stimulus intensity becomes a significant variable, with respect ot the accuracy measure.

Third, for the temporal order task, SOA values less than 28 msec and greater than 4 msec do not result in any change in the number of correct responses. Additionally, within that range of SOA values, stimulus intensity has no influence on the accuracy measures.

Fourth, for the fusion task, stimulus intensity and SOA interact, with interaction occurring between the 4- and 12-msec SOA values, observed by the response time data. After the 12-msec SOA value, three parallel intensity functions are observed, as presented in Figure 2.

Fifth, for the temporal order task, stimulus intensity and SOA have no effect on the response time.

These five findings will be integrated in the following section of this report.

The Integration

In order to integrate the previous results, a model that enables one to use both accuracy measures and response time measures must be used. Such a model has been developed by Teichner (1974). Additionally, Teichner's model provides for the independent variable of stimulus intensity. Consequently, it is this model that will be used to integrate the present results.

Teichner's model, presented in Figure 4, assumes that a certain amount of evidence about a stimulus has to be accumulated before a response can be initiated. The abscissa represents the amount of time necessary for the evidence to accumulate, while the ordinate represents the cumulative amount of evidence. Accumulation of evidence continues until a criterion amount of evidence, represented by the solid horizontal line is reached. Once the accumulation of evidence, represented by the slanted line, reaches criterion, a response is initiated.

Superimposed on the model is Stroud's concept of psychological time. According to Stroud, psychological time, unlike physical time, can be conceptualized in terms of discrete units or moments. While physical time is a continuous dimension, psychological time is a quantal entity and as such all events that fall within one unit are perceived as occurring at the same physical time. As a result, while various events may be sequentially arranged in physical time, in psychological time they appear to be simultaneous events.

The psychological moment is depicted in Figure 4 as the area between the dotted vertical lines. If the evidence from two stimuli cross the criterion within the same psychological moment, then it is assumed that they will be perceived as one stimulus. Likewise, if the evidence from the two stimuli cross the criterion in two different psychological moments, then they will be perceived as two stimuli.

Grice (1968) and Teichner and Krebs (1972) hypothesized that the accumulation of evidence is a function of stimulus intensity. That is, as the intensity of the stimulus increases, the amount of time required for the accumulation of evidence to reach the criterion decreases. The increase or decrease in intensity is reflected in two ways. First, with a change in intensity, the slope of the line representing evidence changes; a steep slope represents an

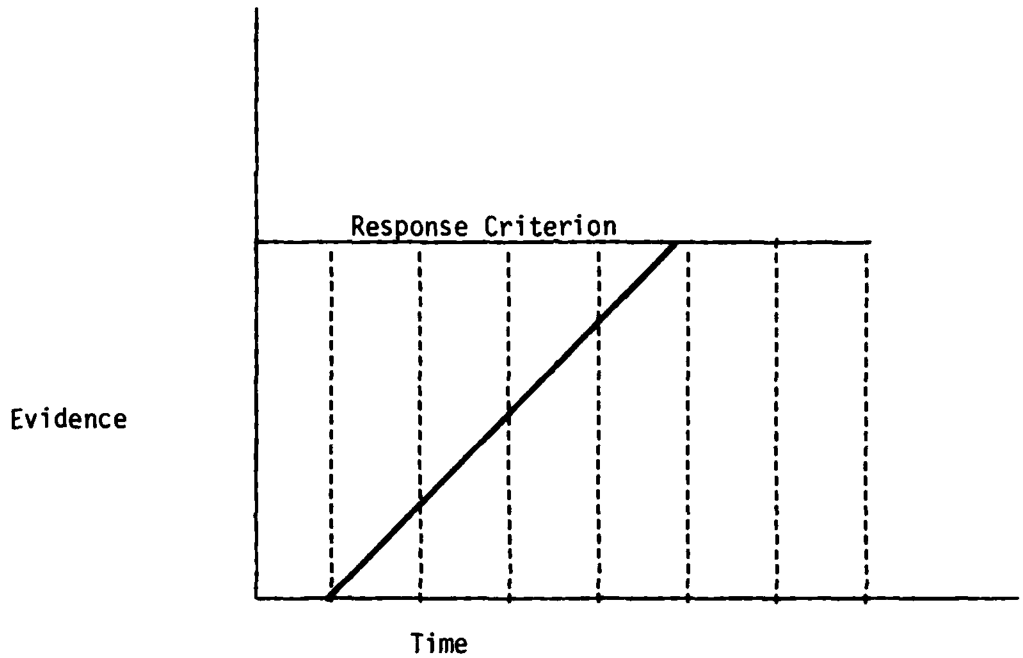

Figure 4. Teichner's (1974) response criterion model.

intense stimulus, a shallow slope represents a weak stimulus. Second with a change in intensity, the criterion also changes; a higher criterion represents an intense stimulus, while a lower criterion represents a less intense stimulus. Therefore, Teichner and Krebs (1972) state that the criterion as well as the accumulation of evidence is dependent on stimulus intensity.

Several modifications of Teichner's model appear to be warranted. First, since the original definition of the psychological moment appeared to use data obtained from only one type of perceptual judgments, namely simultaneity judgments, the duration of that unit of psychological time was estimated by Stroud to be on the order of 100 msec. The investigations by Hirsh and Serrick on temporal order and the literature review by Fraisse seem to imply that other types of psychological moments, which are task dependent, exist. Therefore, the fusion task threshold; i.e., moment, from the present study, appears to be a function of stimulus intensity. The temporal order threshold or moment derived from the present study is not dependent on stimulus intensity, and appears to be larger than the moment associated with the fusion task. Consequently, it is assumed that two duration moments, each associated with their respective tasks, exist.

Additionally, since the response time is an indicant of the criterion, a modification of the criterion concept of Teichner's model must also be proposed. Given the different influence of SOA and stimulus intensity on the response time measures obtained from the two tasks, it is proposed that two criteria exist.

Given those two modifications to Teichner's model, the data appear to be explained by the model with the following assumptions:

1. It is assumed that the rate of evidence accumulation is a function of stimulus intensity. That is, the line representing evidence accumulation has a steeper slope as intensity increases.

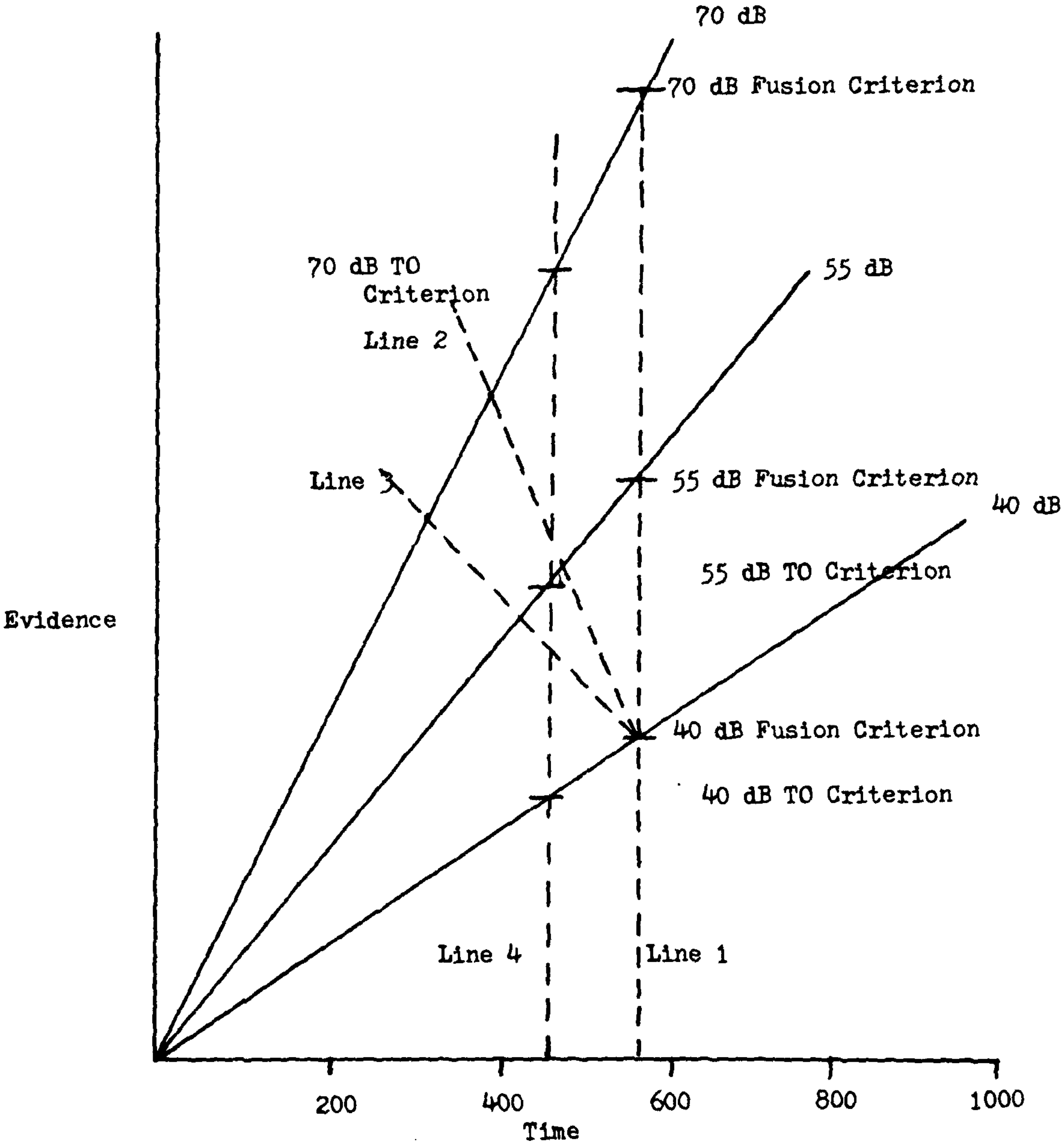

Figure 5. The influence of SOA on the criterion for the fusion and temporal order tasks

2. It is assumed that the criterion associated with a more intense stimulus assumes a higher value at a 0-msec SOA value than a less intense stimulus.

3. It is assumed that as stimulus onset asynchrony increases, the criterion decreases a decreasing amount.

Figure 5 was constructed using those three assumptions. The _y_ axis represents cumulated evidence. The _x_ axis represents time. The three solid slanted lines represent the accumulation of evidence associated with the three intensity values used in this investigation. The line with the steepest slope represents the 70-dB intensity value, the next steepest slope represents the accumulation of evidence associated with the 55-dB intensity value, and the line with the shallowest slope represents the accumulation of evidence associated with the 40-dB stimulus.

Applying the second assumption, that the higher the intensity value the higher the criterion level, as well as noting that the 0- to 4-msec SOA values resulted in no significant fusion task response time differences as a function of stimulus intensity, a line parallel to the _y_ axis, Line 1, is drawn. The intersection of Line 1 with the three lines representing the accumulation of evidence for the three intensity values represents the criterion values for the three intensity values associated with the fusion task.

Applying the third assumption, that the criterion level decreases a decreasing amount as SOA increases, two other points along the 70-dB evidence accumulation function are selected. Both of these points represent criterion levels associated with increasing SOA values. Point 3 is one-half the distance, on the 70-dB function, from Point 2 to Line 1. Since the intersection of Line 1 with the 70-dB function represents the 0- to 4-msec SOA value, it was arbitrarily selected to represent the 4-msec SOA value. Point 2 represents

a 12-msec increase in SOA, and Point 3 represents a further 12-msec increase in SOA. As a result, Line 1 represents the 4-msec SOA value, Point 2 represents the 16-msec SOA value and Point 3 represents the 28-msec SOA value.

Since the response time assoicated with the 40-dB intensity value was not influenced by SOA, a dashed line connecting Point 2 and the criterion level of the 40-dB stimulus was drawn, Line 2. Likewise, a dashed line, connecting Point 3 and the criterion level of the 40-dB stimulus was drawn, Line 3.

If the assumptions of the model and the model are correct, then a function relating the intersection of the lines by intensity values should result in an SOA by intensity interaction for the fusion task, similar to that observed in the experiment, and presented in Figure 2.

Figure 6 was derived using the response times, intensity values and SOA values of Figure 5. While the absolute values of the response times are not correct, the shape of the interaction is strikingly similar to the actual function presented in Figure 2.

Given the previous discussion for the fusion task response times, the response time data from the temporal order task must also be fit to the model. The separate analysis of the response time data for the temporal order task resulted in no significant differences in intensity or SOA. As a result, the criterion levels associated with the three intensity levels must be arranged such that stimulus intensity is directly related to the criterion level.

Moreover, the response time data for the 70-dB stimulus intensity condition for each task can be used to locate the temporal order criterion level on the two other intensity fucntions. Recall that the fusion task resulted in a slower, then the same and then a faster response time than the latencies associated with the temporal order task. The transition point from slower to the same was approximately the 7-msec SOA value. This value is approximately

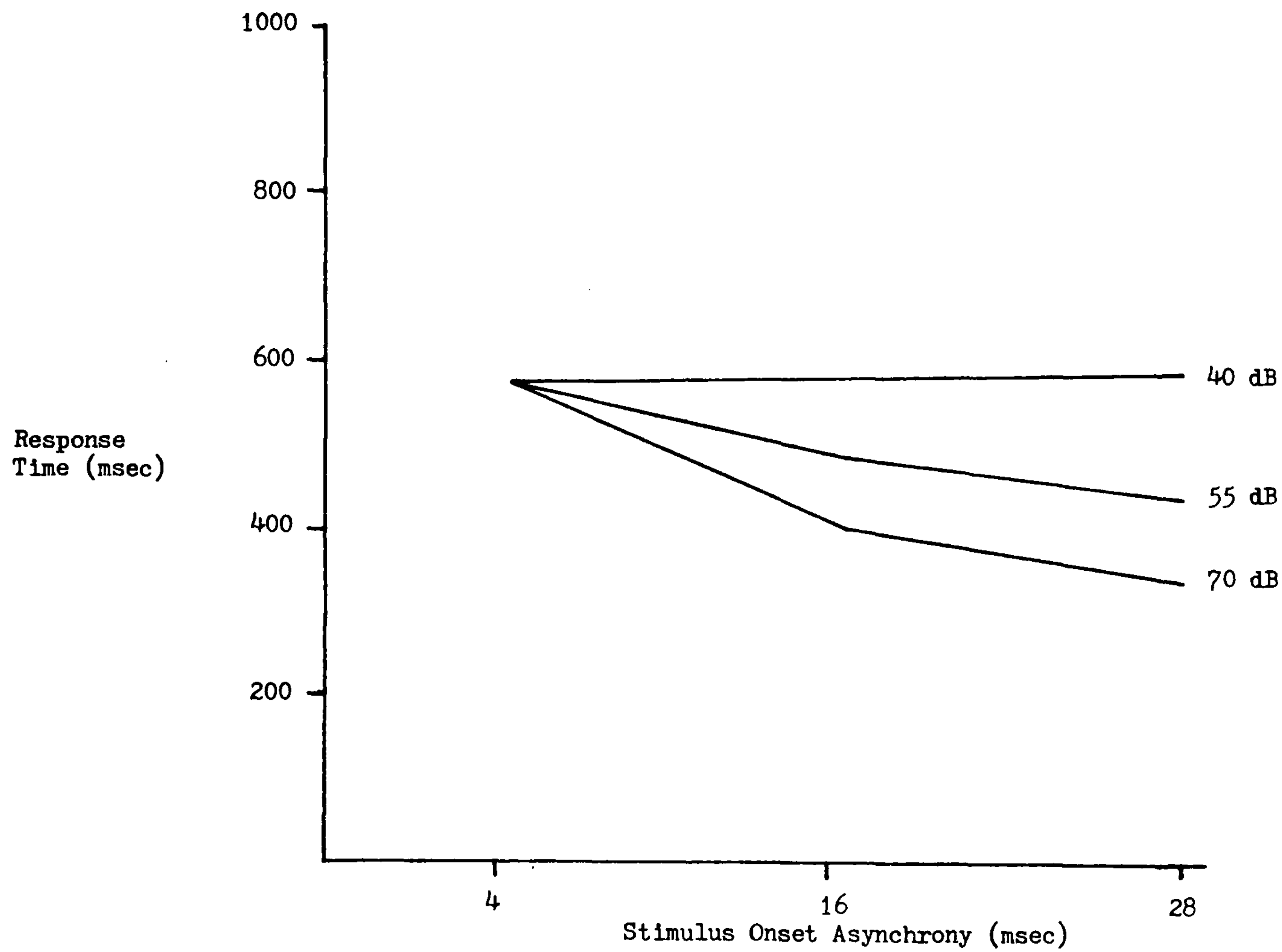

Figure 6. The predicted stimulus onset asynchrony by intensity interaction for the fusion task.

two-thirds of the distance, on the 70-dB function from Point 2 to Line 1. The intersection of Line 4 with the three intensity functions represents the criterion levels associated with the temporal order task at each intensity level. Since the temporal order criterion is stationary for the SOA values used in this experiment, as inferred from the response time analysis, a comparison between the predicted task by intensity by SOA interaction and the actual interaction observed in the experiment (see Figure 3), can be performed.

Figure 7 presents the response times associated with each task as a function of SOA, for each intensity value, as derived from Figure 5. Once again the absolute response time data is not comparable to the actual data, although it could be simply by fixing Lin 1 to the mean response time data across intensity and SOA values of 0, 1, 2, and 4 msec obtained from the experiment. Nevertheless, the three between-task functions illustrated in Figure 7 approximate the shape of the actual functions.

Given the assumptions of the model it appears that the response time data can be approximated to a high degree.

Given the existence of two criteria, one associated with the fusion task and the other associated with the temporal order task, and the existence of two duration moments, one associated with the fusion task and the other associated with the temporal order task, a statement regarding the location of these structures given the onset of two temporally displaced stimuli must be made. The following discussion will be limited to the 70-dB intensity value.

With an onset separation less than, or equal to 4 msec, given two equally intense stimuli, the temporal order criterion and fusion criterion are arranged as in Figure 8a. This figure illustrates a lower temporal order criterion. The $\underline{x}$ axis represents time, while the $\underline{y}$ axis represents the cumulative amount of evidence. The area between the $\underline{x}$ axis and the temporal order

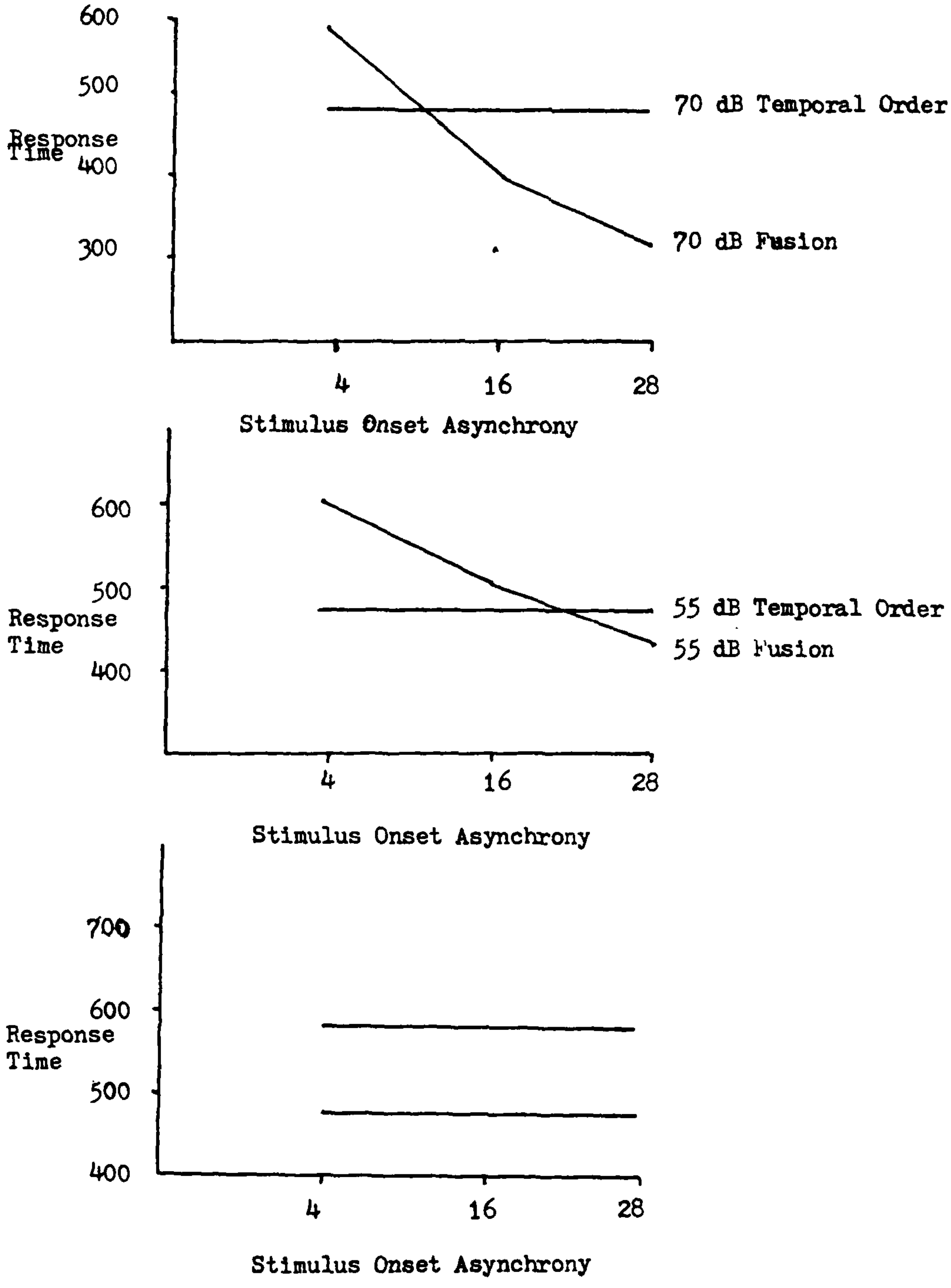

Figure 7. The predicted stimulus onset asynchrony by task by intensity interaction.

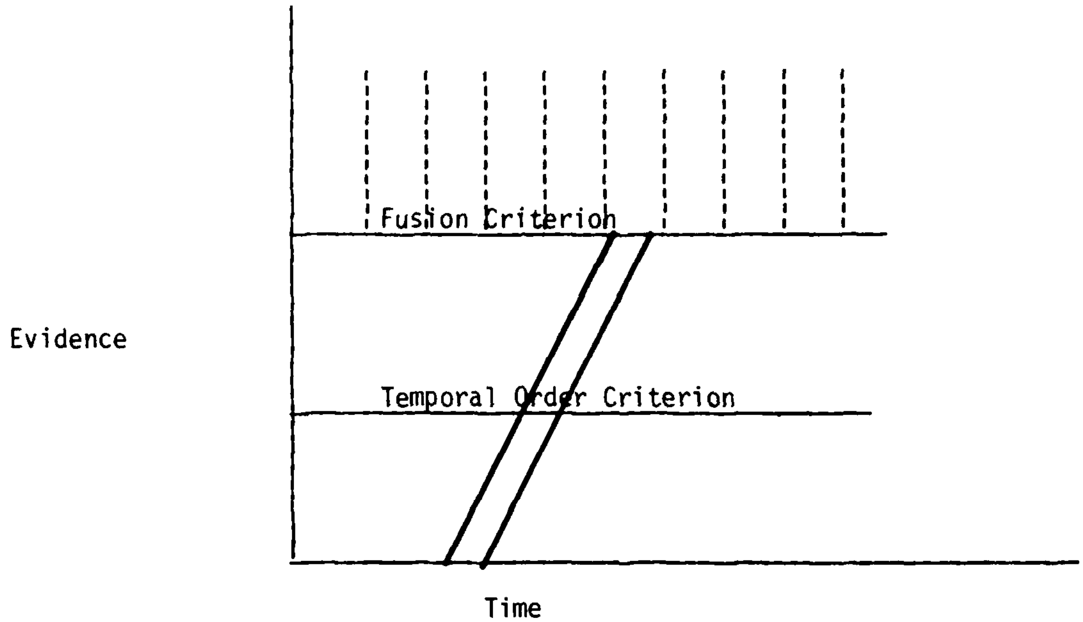

Figure 8a.

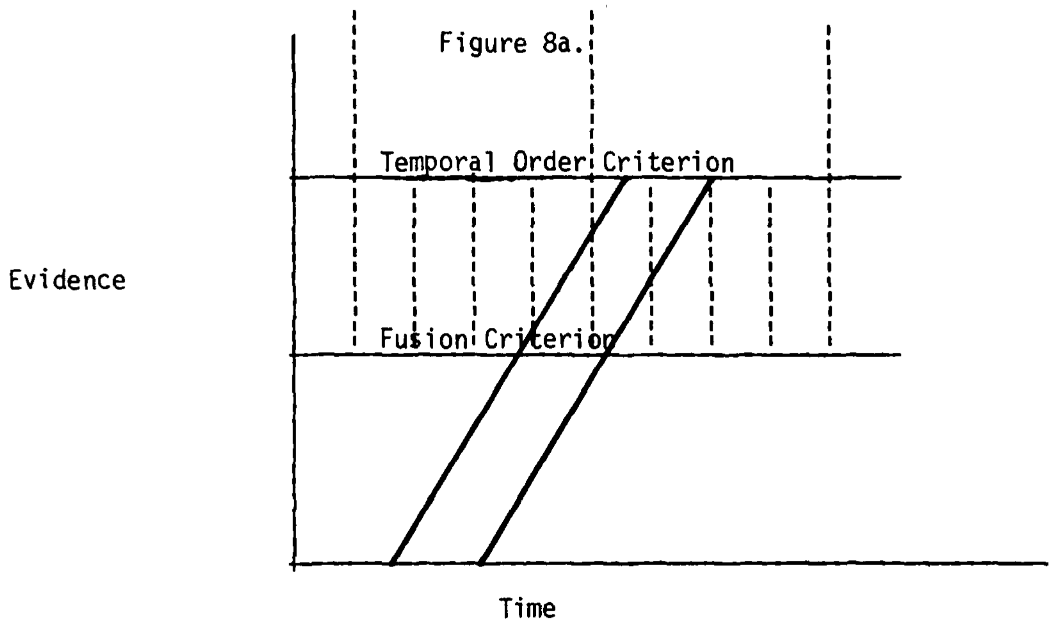

Figure 8b.

Figure 8. The hypothetical arrangement of the criteria.

criterion represents the minimum build-up of evidence (Grice, 1968). The area between the temporal order criterion and the fusion criterion represents an additional amount of time. Hypothetically, another duration moment may be operating at this level, since stimulus intensity appears to be important in the accuracy of temporal order judgments for SOA values less than 4 msec (see Figure 3). Additionally, studies investigating lateralization judgments, the perception of one stimulus and its location from the midline, suggest similar types of processes. Nevertheless, if the evidence from the two stimuli cross the temporal order criterion, true order information can not be ascertained. True order information implies that two events occurred. Only if the accumulation of evidence about each stimulus crosses the fusion criterion within two fusion moments, could a true order judgment be performed.

With larger SOA values, the criterion associated with the fusion task decreases so that both the temporal order criterion and the fusion criterion assume the same value. However, no differences in the perceptions from the short SOA to these somewhat larger SOA values whould occur. However, the response times associated with the fusion task should decrease.

Given still larger SOA increases, the fusion criterion assumes values lower than the temporal order criterion, as illustrated in Figure 8b. Once again, if the accumulation of evidence associated with each stimulus crosses the fusion criterion within one fusion moment, then the perception will be of one stimulus. That is to say, SOA information will be lost. As a result, further evidence accumulation is concerned with the combined evidence-accumulation function. When the accumulation-of-evidence function, associated with the combined stimulus, crosses the temporal order criterion, and falls within one temporal moment, the result will not be a true temporal order judgment. That is, since only one stimulus was perceived, a judgment of order concerning

two stimuli cannot be made. If the accumulation of evidence associated with each stimulus crosses the fusion criterion within two different fusion moments, then the resulting perception, at the temporal order criterion, may simply be the perception of two stimuli with no order, or the perception of two stimuli with order. The order perception depends on the occurrence of the temporal order moments in relation to the time that the accumulation of evidence function reaches the temporal order criterion.

While the previous discussion has concentrated only on the 70-dB stimulus intensity value, a similar decrease in the criterion level for the fusion task is expected, given larger SOA values coupled with less intense stimuli.

Areas for Further Research

In order to ascertain whether or not the temporal order threshold, or moment, is a function of stimulus intensity, SOA values larger than 28 msec must be used. Several of the process mentions in The Integration section of this report are based on the assumption that the temporal order moment is a function of stimulus intensity, and that the duration of this moment is greater than 28 msec. Since lateralization judgments (Harris, 1974) and fusion judgments are dependent on stimulus intensity, it seems plausible that the temporal order threshold is also a function of stimulus intensity. Furthermore, Rutschmann (1973) suggests that the temporal order threshold is a function of stimulus intensity.

This investigation has shown that the criterion level is a function of the task being performed, stimulus intensity and SOA. Other variables, such as payoffs and risks, if they serve to activate the system, should be manipulated to investigate the changes that occur in the criterion level and the moment duration. Furthermore, other parameters of the stimulus need to be incorporated into the model. Of primary interest is the role that stimulus duration and stimulus frequency play in the processing of auditory stimuli.

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